CRANFIELD UNIVERSITY

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Risks to health of carbon monoxide and other combustion gases in energy efficient homes

IEH
Cranfield Health

MSc by Research
Academic Year: 2010 - 2011

Supervisor: Dr Derrick Crump
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ABSTRACT

Revisions of the UK Building Regulations are resulting in changes in the design, construction, heating and ventilation of new and refurbished homes. There are concerns that inadequate ventilation of these energy efficient homes could result in increased levels of indoor pollutants. This study considers the possible risk to occupant health due to exposure to combustion by-products, such as carbon monoxide (CO).

Measurements of combustion pollutants during the 2010/11 heating season were undertaken in 14 homes built/refurbished in accordance with 2006 Building Regulations or to a higher standard of energy efficiency, as well as 5 older homes over a two week period.

No WHO indoor air guidelines for CO were exceeded in any home. It was found that there was a significant difference between CO and nitrogen dioxide in the kitchen and the bedroom of the main study homes. Modelling of CO demonstrated how situations of low ventilation combined with high and also moderate source emission rates could potentially lead to air quality guidelines being exceeded. Combustion, heating elements and some aerosols were found to greatly increase the number of ultrafine particles (UFPs). Currently, no guidelines for UFPs in air are available and there is limited literature reporting their measurement.

The air quality measurements do not show that energy efficient homes pose greater risks to health of occupants from combustion pollutants than other homes. However, modelling suggests some scenarios could produce exposure to CO exceeding health based guidelines. The study is considered as a preliminary investigation, not representative of the wide range of different house types and occupant behaviours that may influence pollutant levels and exposure of occupants. It does provide valuable indicative data and identifies a need for further work as current knowledge about indoor air quality in energy efficient homes is limited and possible risks to health have not been fully evaluated.

Keywords:

Gas appliance

Biomass

Ultrafine particles

Code for Sustainable Homes

Indoor air

Nitrogen dioxide

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ABBREVIATIONS

AD	Approved document
BaP	Benzo[a]pyrene
BS	British Standards
CO	Carbon monoxide
CO_2	Carbon dioxide
COHb	carboxyhaemoglobin
CHP	Combined heat and power
DNPH	Dinitrophenylhydrazine
EPA	Environmental Protection Agency
FID	Flame ionisation detector
GC	Gas chromatography
HPLC	High performance liquid chromatography
HVAC	Heating, ventilation and air-conditioning

IAQ	Indoor air quality
ISO	International Standards Organisation
MS	Mass spectrometry
MVOC	Microbial volatile organic compound
NDIR	Non-dispersive infrared
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_X	Oxides of nitrogen
PAH	Polycyclic aromatic hydrocarbon
PID	Photo ionisation detectors
PM	Particulate matter
POM	Particulate organic matter
SBS	Sick building syndrome
SEM	Standard error of the mean
SO_2	Sulphur dioxide
SVOC	Semi volatile organic compound
TVOC	Total volatile organic compounds
TWA	Time weighted average
UFP	Ultrafine particles
UPC	Ultrafine particle counter

UV	Ultraviolet
VOC	Volatile organic compound
VVOC	Very volatile organic compound
WHO	World Health Organisation

UNITS

ach	Air changes per hour (h^{-1})
atm	Atmosphere
cm	Centimetre
g min^{-1}	Grams per minute
kg	Kilograms
l s^{-1}	Litres per second
m	Metre
m^3	Cubic metre
m s^{-1}	Metres per second
mg	Milligrams
mg m^{-3}	Milligrams per cubic metre
nm	Nanometres
ng m^{-3}	Nanograms per cubic metre
ppm	Parts per million

ppm h^{-1}	Parts per million per hour
pt cm^{-3}	Particles per cubic centimetre
℃	Degrees Celsius
Mm	Micrometre
µg m^{-3}	Micrograms per cubic metre

1 Introduction and literature review

1.1 Overview

People spend the majority of their time indoors most of which is spent in the home; typically 80 – 90% in developed countries (Koistinen *et al*., 2008; Bone *et al*., 2010). Particular groups such as the young, the elderly and those with ill health may spend even more of their time in the indoor environment. The quality of the indoor air is therefore a major determinant of the exposure people have to air pollutants.

The UK government proposes to cut carbon emissions by 80%¸ compared to that of 1990, by 2050 in all new homes built from 2016. The homes will be carbon neutral[1] and will have their sustainability and construction measured against nine categories, which include health and wellbeing but indoor air quality (IAQ) is not directly addressed, and will be rated as levels 1 – 6 based on their overall sustainability. Airtightness is to be increased in order to lower thermal loss, which could result in reduced ventilation and lead to a decline in IAQ posing potential health hazards to occupants. House builders and developers appear optimistic about their abilities to comply with increased requirements from standards of airtightness but have expressed concerns about the resultant air quality which may affect the welfare of the occupants and also the required service, maintenance and the level of understanding of mechanical ventilation systems (Davis and Harvey, 2008).

Combustion appliances, such as gas cookers and boilers, are a source of indoor air pollution and pose a health risk if there is inadequate ventilation; carbon monoxide (CO) is singled out from other gases such as nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) as it poses a greater health risk: CO is the

[1] Net emissions over the course of a year from the home itself and the regulated activities (i.e. energy used for water heating, lighting, pumps and fans), that take place within the home are zero.

leading cause of accidental and intentional deaths related to poisoning where intoxication can occur as a single or repeated exposure (WHO, Regional Office for Europe, 2010). Exposure to combustion generated pollutants such as CO, NO_2, particles and environmental tobacco smoke can lead to a range of health effects including cardiovascular diseases, which are the leading cause of deaths in industrialised countries (Crump *et al*., 2009). There is little information available about monitored levels of these pollutants in new, energy efficient homes and investigation is required to assess the possible risks to health.

Combustion gases in homes can be emitted from space heaters (including flueless appliances) using solid, liquid and gas fuels, as well as water heaters, cooking activities, tobacco smoking and vehicle emissions, particularly if the vehicle is kept in an attached garage. Outdoor sources include motor vehicle traffic, industry and natural events (such as volcanic activity, oxidation of methane and other organic compounds, forest fires and as a metabolic product of plants and vegetation); as well as entering the building through ventilation and infiltration some releases may occur close to ventilation intakes and thereby have a strong impact on indoor concentrations (U.S. EPA, 2000a). The main products of combustion are carbon dioxide (CO_2) and water vapour but other products occur depending upon the fuels used, air content and the completion and efficiency of the combustion process. CO_2 and water vapour are relatively harmless to human health, in high concentrations in a confined space CO_2 will act as an asphyxiant and high water vapour content contributes to dampness and mould growth (Communities and Local Government, 2004). Environmental tobacco smoke can release over 3800 different gases and particulate matter (PM), where the particulates are collectively known as tar, a known carcinogen (Communities and Local Government, 2004); although banned in enclosed public spaces in the UK, tobacco smoking can be a major source of pollution and poor air quality in the home.

Alternative sources of power for sustainable homes involve the use of microgeneration and renewable energy. Biomass fuel systems usually refer to those fuelled by wood and are only considered a renewable source of energy if

the trees used are replaced (Fisher *et al*., 2008). Possible health concerns could arise with the use of these new systems and their combustion products along with increased building airtightness.

This study considers the possible increased risk to occupant health due to exposure to incomplete products of combustion in energy efficient homes. It reviews literature on sources, occurrence and health effects of CO, NO_2, volatile organic compounds (VOCs), SO_2 and particles in air, the characteristics of energy efficient homes that could impact indoor air pollution and the use of models to predict indoor air pollution. There is a dearth of data on air quality in new homes for conducting an assessment of risks to health and therefore a field study has been conducted that used various instruments to take measurements of carbon monoxide and other combustion products in 14 homes built or refurbished since 2007. These included homes built as recently as 2010 and innovative designs that are considerably more energy efficient than properties built prior to 2006 changes in the Building Regulations. A group of older homes were also monitored as control properties. A protocol has been developed to set out a procedure for the recruitment and monitoring processes, including letters to be sent to contact potential participants and forms requiring completion during the monitoring process.

Results of the monitoring are discussed and an indoor air pollution model is applied to predict levels of CO with varying indoor emission rates and air exchanges and these are compared to air quality guidelines. The findings are discussed to assess the possible risks of poor air quality arising from combustion processes in energy efficient homes.

1.2 Literature Review

1.2.1 Strategy used for literature review

To identify key papers, the search tool Scopus was used (Appendix A). Product information, standards and websites were also reviewed as well as key authorities on air quality, indoor air and homes such as the World Health

Organisation, (WHO), the US Environmental Protection Agency (EPA) and the UK's Communities and Local Government. Principal documents were reviewed such as Air Quality Guidelines (WHO, Regional Office for Europe, 2010; WHO, Regional Office for Europe, 2000; WHO, Regional Office for Europe, 1987), Carbon Monoxide (WHO, 1999), Air Quality Criteria for Carbon Monoxide, (U.S. EPA, 2000a), Indoor Air Quality in Highly Energy Efficient Homes – a review (Crump *et al*., 2009) and Sustainable new homes (Communities and Local Government, 2009a).

1.3 Energy efficient homes

New homes are built to greater standards of energy efficiency for the purpose of conservation of energy. This includes increasing the building's air tightness, which unless windows or mechanical ventilation are used, will result in low air exchange rates between indoor and outdoor air (Offermann, 2010). The construction of new energy efficient homes is being driven by UK government policy in order to reduce energy consumption and greenhouse gas emissions as well as enable greater use of renewable fuel sources and to be more sustainable. The Government is also encouraging the refurbishment retrospectively of existing homes to improve their energy efficiency and enable use of new energy efficient technologies. Energy efficient homes enable lower running costs in comparison with existing conventional homes due to their thermal insulation and renewable and sustainable technologies.

1.3.1 Zero carbon

The 1997 Kyoto protocol required industrialised countries to advance to a 5% reduction in greenhouse gas emissions and this was the first collaborative initiative to try to reduce carbon emissions globally (Prins and Rayner, 2008). As a result of this, the UK is committed to reduce the emission of its greenhouse gases by 12.5% by 2012 from that of 2008 (Wilford and Ramos, 2010). Aims for UK energy suppliers to achieve targets for reduction through methods such as insulation, energy efficient light bulbs and promotion of

microgeneration and biomass fuels are being driven by initiatives such as the Energy Efficiency Commitment and the Carbon Emissions Reduction Target.

The 2008 Climate Change Act has revised the reduction of emissions from 60% to at least 80% by 2050 compared to that of the 1990 baseline (Acts of the UK Parliament, 2008). Buildings and housing play a major part in carbon emissions, with 30% of the total UK energy use and 27% of UK carbon emissions coming from the housing stock (Davis and Harvey, 2008). Other important acts in cutting energy use and carbon emissions include the Energy Act of 2008 where its key elements include renewable energy, smart meters and carbon capture and storage (Wilford and Ramos, 2010). The Stern review also drives policy to cut carbon emissions by summarising the scientific evidence for global warming and the necessity for an urgent response, recommending emissions to be cut by energy efficiency measures, changes in demand and adoption of clean energy and transport (Stern, 2006).

Approximately 80% of energy in homes is used for space and water heating. Solutions to this include more efficient appliances, insulation, draught proofing and double glazing (Wilford and Ramos, 2010). A zero carbon home is one of zero net emissions of CO_2 from all energy used in operation of the home covered by the Building Regulations, such as heating, fixed light and hot water and does not include unregulated emissions such as those from plug in appliances and from cooking. This incorporates high energy efficiency and on-site reductions and all new homes built from 2016 will be required to be zero carbon. It is expected that one third of homes that will be occupied in 2050 will be newly built. New buildings and structural changes in the UK must comply with Building Regulations, such as Part L: Conservation of Heat and Power, and Part F: Ventilation, with approved documents providing guidance on how compliance may be achieved (Bone *et al*., 2010). Approved Document part F: ventilation (AD F) recommends ventilation provisions to control moisture and indoor air pollutants. Building a Greener Future, a consultation document, set out the target for zero carbon homes through Part L of the Building Regulations

with benefits to the occupants including lower fuel bills and warmer homes in the winter (Communities and Local Government, 2007).

1.3.2 The Code for Sustainable Homes

The Code for Sustainable Homes, introduced in 2007 to England and subsequently adopted by Northern Ireland and Wales, aims to improve sustainability of new homes. New homes from 2008 are mandatorily rated against nine categories: energy and CO_2 emissions, water, materials, surface water run-off, waste, pollution, health and wellbeing, management and ecology. Of these nine categories, some are weighted more heavily than others, with energy and CO_2 emissions contributing 36.4% to the overall score (Gaze *et al*., 2010), health is included but IAQ is not directly addressed and the effects from the increased air tightness may be overlooked (Bone *et al*., 2010). A home's sustainability is rated from 1 – 6 (Code level 6 being zero carbon) against these categories with minimum targets required to be achieved for each Code level.

The target of zero carbon homes by 2016 should be met with the interim steps for Code levels 3 and 4 by 2010 and 2013 respectively; the way in which developers achieve the requirements for the Code is flexible (Communities and Local Government, 2009a). For certified homes in compliance with the Code, explanations of how this was achieved along with the Energy Performance Certificate, which depicts the environmental impact rating, must be provided.

Homes achieving Code level 1 represent a 10% improvement in carbon emissions over Building Regulations for the 2006 AD Part L (conservation of fuel and power), whereas the 2016 target of Code level 6 zero carbon homes represents a 150% improvement to the regulations. Table 1-1 summarises the percentage improvement over 2006 regulations and the timetable for implementation.

Table 1-1: Code for sustainable homes - steps to zero carbon new homes and corresponding Code levels

(Adapted from: Communities and Local Government, 2009b p.26)

Code level	Current energy standard (percentage improvement over 2006 Part L)	When equivalent change in regulations is due
1	10%	-
2	18%	-
3	25%	2010
4	44%	2013
5	100%	-
6	Zero carbon (equivalent to 150%)	2016

The commitment to zero carbon homes was reconfirmed by the government in the summer of 2010, which commissioned a Task Group within the Zero Carbon Hub for recommendations on carbon compliance limits to help define the regulations that will be applied in 2016. Carbon compliance is a target for carbon emission levels for a home and is achieved by both the performance of the building fabric and the performance of low and zero carbon heat and power technologies (Zero Carbon Hub, 2011). Using modelling, the Task Group deduced that the previous proposal for a 70% reduction in carbon emissions is not practical in all cases and the performance of different build forms (i.e. detached houses and high-rise apartments), are different and should therefore have different and more appropriate levels.

The broad factors affecting the carbon compliance are technical considerations such as feasibility, commercial factors such as cost and policy issues such as constraints due to other policies. Tightening of carbon compliance for the Building Regulations will be next reviewed in 2013. When carbon compliance is

further tightened in 2016, it is expected that the effects will not be seen immediately as sites being built before the change will not have to comply, by 2020 the majority of newly completed homes will meet this new standard.

Benefits for the environment of new homes abiding to the Code include reduced greenhouse gas emissions and adaption to climate change. Homes are meant to be of lower running cost and improved comfort and wellbeing with the new homes being a healthier place to live (Communities and Local Government, 2006). In higher Code level homes, the greater airtightness will probably require mechanical ventilation to achieve adequate ventilation with the possibility of reducing energy requirements. The use of mechanical ventilation may raise concerns with risk of failure, lack of maintenance and ease of use which may result in poor air quality. In a recent paper, the dilemma of risk of increasing CO poisoning in energy efficient homes due to poor ventilation resulting from efforts to save energy is weighed up against the fact that reduced reliance on fossil fuel will remove some sources of the gas (Bone *et al*., 2010).

Achieving Code level 4 will probably require biomass or renewable fuel and energy sources (Gaze *et al*., 2010). The Renewable energy strategy places biomass among the forefront of fuels and technologies to be used in order to achieve the target of supplying 15% of the UKs energy from renewable sources by 2020 (The Department of Energy and Climate Change, 2009).

1.3.3 Biomass fuel

Biomass fuel can be used as an alternative to fossil fuel, with close to net zero carbon emissions; its use could help achieve credits required for the higher levels of the Code for Sustainable Homes due to the great reduction of CO_2 emissions in comparison to standard fuelled systems used today (Gaze *et al*., 2010). Although the fuel may be transported over great distances it may still be regarded as low carbon as alternatively the biomass often goes into land fill sites where it decomposes to generate methane, a more potent greenhouse gas than CO_2 (National Building Specification, 2006).

Biomass fuels are organic fuels, commonly from wood sources, such as forest residues and energy crops. These sources are converted to a manageable form that can be inputted to heat or generation plants and are usually in the form of wood chip, logs and wood pellets (National Building Specification, 2006). Biomass can be thought of as stored solar energy captured by growing organic matter, where its energy is released by such methods as combustion (Carbon Trust, 2009). Wood pellets offer higher energy value per unit of weight than wood chip and logs as the pellets are compacted high density woods with low moisture content.

Biomass can be used to fuel appliances such as boilers, cookers and central heating, used in standalone room heaters and also for combined heat and power (CHP) for generation of heat and electricity. It is thought that biomass fuelled CHP is still being developed and could provide significant cuts to emissions of CO_2 (Gaze *et al*., 2010). Efficiencies greater than 80% have been achieved for appliances but are not currently widely used in the UK (National Building Specification, 2006). For example Woodpecker Energy (UK) Ltd currently has a biomass boiler which is 94% efficient (Woodpecker Energy (UK) Ltd, 2010). An electricity supply may still be required in some appliances to power control systems, fans and fuel feeders (Fisher *et al*., 2008).

Oxides of nitrogen (NO_X) emissions from biomass sources are higher than that of gas fuels used today as well as other possible fuel sources that could be used to achieve Code level 5 or higher, such as low NO_X gas boilers and gas-fired communal CHP systems (Gaze *et al*., 2010). Along with NO_X emissions, PM and airborne pollutants such as polycyclic aromatic hydrocarbons (PAHs) and heavy metals may be an issue with waste derived fuels as the emissions from biomass fuels differ largely from fossil fuels, therefore air quality assessments and typical emissions for fuel types need to be investigated further (Holford, 2010). Emissions of CO, PM and PAHs from biomass fuels depend upon the completeness of combustion and NO_2 and SO_2 emissions are dependent on the individual fuel composition (Environmental Protection UK, 2010).

Suggestions for use of biomass fuel systems include communal systems, such as a communal boiler, but problems arise as this may not be suitable for all environments with issues of maintenance, fuel storage and delivery and space needed for the plant (Gaze *et al*., 2010). Health concerns lie with modern homes being too air tight and not all biomass equipment being suitable for operation in smokeless zones and over sizing of equipment can result in low output levels which may lead to incomplete combustion, tar formation and acid formation which can shorten the life of the system (Fisher *et al*., 2008).

A Communities and Local Government report on CO detectors recommended that CO detectors are required with the installation of all new solid fuel combustion appliances, such as biomass and coal fuel (Communities and Local Government, 2009b). CO levels can be 100 times greater in flues of solid fuel appliances than in gas appliances, suggesting small leakages may produce unacceptable or dangerous levels of CO within the home. The report also suggests open fires may produce low, acceptable levels of CO within the home that may exist in the indoor air for extended periods, which may worsen as dwellings become more air tight in adopting new regulations.

Approximately one third of the global population uses biomass fuels, indoor air pollution generated from biomass combustion has the capacity to greatly influence global mortality and morbidity, annual deaths of lung cancer accounted to exposure to biomass smoke is estimated to be 1.5 % of the one million plus deaths (Kim *et al*., 2011). Developing countries may account for greater mortality and morbidity numbers due to the use of unprocessed biomass fuels such as animal dung, which can generate greater levels of indoor air pollution from incomplete combustion.

The use of biogas was assessed by literature review to establish likely composition, emission and toxicology of its use (Leroux *et al*., 2009). Compared to natural gas, it was found that the use of purified biogas from household and organic waste landfills did not present further risks to health for users before and after combustion. The main pollutants emitted are likely to be CO, NO_x and unburned components such as VOCs and particles.

1.4 Indoor air quality

Poor quality of indoor air is of concern because of the possible health implications for building occupants. There is a lack of knowledge about IAQ in new, more air tight homes.

Indoor air is rarely static with concentrations of pollutants varying from room to room depending upon the type and strength of the source, human activity, ventilation rate, infiltration, external/internal climatic conditions, chemical reactions and sorption, degree of mixing of the air and possible sinks e.g. materials that can reversibly/irreversibly absorb chemicals from the air (British Standards Institution, 2006).

People spend the majority of their time indoors, approximately 90% (Carslaw *et al*., 2009), much of that time is spent in the home, therefore indoor air plays a major role in determining human exposure to airborne pollutants (Crump *et al*., 2002). Sources of indoor air pollution include infiltration of outdoor air, building and renovation materials, combustion appliances, consumer products, activities and bioeffluents such as CO_2 and body odour from people themselves. Activities can include tobacco smoking, burning incense, decorating and renovating and user preferences on purge ventilation. Indoor air pollutants can be carcinogens, such as formaldehyde and radon, and biological/chemical contaminants, such as endotoxins and combustion products (Dales *et al*., 2008).

Off-gassing emissions are air pollutants resulting from indoor materials, they include VOCs and formaldehyde, which can be released from materials such as wood, paints and glues. Emissions are higher in newer homes and this is because of emissions from newer materials which decay over time (Dales *et al*., 2008). In developing countries cooking and heating activities using biomass fuels is a major cause of acute respiratory infection (Myers and Maynard, 2005). Sources can be continuous, such as off-gassing which may vary depending upon temperature and humidity, or intermittent where the strength may vary, such as gas cooking, which may emit irregular emissions but usage from

occupants may result in a regular pattern observed (British Standards Institution, 2006).

Singer *et al*., (2011) examined the capture efficiency of three cooker hoods used in conjunction with a natural gas cooker. They found that cooker hoods can effectively remove pollutants when operated on the highest speed and cooking is performed on the back hobs, but the noise generated probably impairs their use and effectiveness. Under the ideal conditions used, lower speed settings still captured more than half of the burner exhaust when using the back burners but less than 40% when the front burners are used and the authors note that in real homes not under the ideal conditions, capture efficiency would be less efficient, where poor design and installation and blocked flows could interfere with the capture efficiency along with the movement of the cook, opening of windows and the high power setting of the burner and use of several burners at a time. The authors concluded that the lowest speed setting, which is quietest and therefore most likely to be used, was not effective in the removal of burner exhaust.

A review looking at changes in IAQ from the 1950s – 2008 (Weschler, 2009), has noted how exposure to toxicants such as CO, SO_2 and NO_2 has generally reduced. Better knowledge and understanding of their risks and the use of cleaner fuels and more efficient appliances have aided this reduction. A decrease in levels of known and suspected carcinogens such as benzene, formaldehyde, asbestos and chloroform has also been observed.

A paper published in 2010 reviewed possible effects on human health and IAQ resulting from changes in UK homes taking place in order to combat and adapt to climate change (Bone *et al*., 2010). The paper states that there is evidence to support a link between the lack of ventilation and poor air quality in new homes, with a survey of UK homes finding higher levels of VOCs in new homes but ventilation was not assessed. It is thought that ventilation is key for achieving suitable IAQ by removing or diluting indoor air pollutants to acceptable levels, but there may also be conflict between energy efficiency strategies and healthy building strategies (Aizlewood and Dimitroulopoulou, 2006).

Indoor environments should preserve health and comfort by supplying adequate fresh outdoor air and by maintaining adequate temperature, humidity and acceptable levels of indoor air pollutants. Sick building syndrome (SBS) is a term ascribed to symptoms related to indoor environmental quality and health and comfort related issues generally in the work place, but some of the symptoms may be experienced in the home (Myers and Maynard, 2005; Gomzi and Bobić, 2009). Contributing factors to SBS were found to include air-conditioning, temperature, humidity, lighting and low ventilation rates. When a fifth of building occupants exhibit 3 or more symptoms associated with being within a particular building and reduction of the symptoms is noticed when leaving the building, this can be an indication of SBS (Gomzi and Bobić, 2009; Bernstein *et al*., 2008). Symptoms of SBS are non-specific and include irritation, fatigue, headaches, airway infection, stuffy or runny nose and nausea.

A collaborative European project, the Health Optimisation Protocol for Energy-efficient Buildings (HOPE) project, showed that energy efficient buildings can be healthy and comfortable and achieve a good indoor environment (Aizlewood and Dimitroulopoulou, 2006). In the UK HOPE study, questionnaires to office occupants showed perceived occupant health could be used to help indicate problems in the office environment. However this was not the case for UK homes where questionnaires did not match actual pollution measurements, the authors proposed that perceived health and comfort cannot be fully explained by these measurements as other factors, such as stress, may come into play. Observation of CO, oxides of nitrogen and aldehyde levels showed these pollutants were not a problem in the sampled buildings.

A Canadian study on health of occupants in energy efficient homes using telephone administered questionnaires, found that occupants of the homes perceived benefits to health regarding IAQ over 1 year of occupancy (Leech *et al*., 2004). In the questionnaire, symptoms such as throat irritation, coughing, fatigue and irritability for all occupants of the home were rated twice over a year where each symptom was graded by frequency of occurrence. In the 52 new

energy efficient homes investigated, the occupant symptom scores improved significantly over the course of the study in comparison to 53 control homes.

An investigation of IAQ in a newly built, affordable, energy efficient home in America concluded that initial testing indicated that meeting the balance of affordability, energy efficiency and IAQ requires a more balanced combination of system operation than keeping a ventilation system supplying fresh air turned on (Wendt *et al*., 2004).

A report investigating IAQ looked into whether homeowners of 108 newly built Californian homes sufficiently ventilate their homes to remove indoor air contaminants (Offermann, 2009). New homes were investigated in the report as it is thought homes with low outdoor air exchange rates may lead to a build-up of air contaminants with indoor sources, with levels exceeding recommended exposure guidelines. It was found that 67% of the homes were below the Californian building code requirement of 0.35 air changes per hour (ach), with a minimum of 0.09 ach observed in one home.

As part of the guidance supporting the Building Regulations for England and Wales Approved Document J (AD J) 'Combustion appliances and fuel storage systems' has recently been updated (Communities and Local Government, 2010a). One of the main revisions is that where fixed site solid fuel appliances are used, a CO alarm is to be installed to warn of the release. This is so that a building can safely accommodate combustion appliances; other requirements included sufficient supply of air should be provided for combustion and cooling, and an appropriate method should be used for discharging the combustion products. The CO alarms should be built to comply with the European standard 50291:2001, Electrical apparatus for the detection of carbon monoxide in domestic premises — Test methods and performance requirements (further details in Appendix B).

BS ISO 16814:2008 (Building environment design — Indoor air quality — Methods of expressing the quality of indoor air for human occupancy) provides guidance on the design of buildings, heating, ventilation and air conditioning

systems and for deriving criteria for new and retrofit buildings for acceptable indoor environments (British Standards Institution, 2008a). No specific methods are given in this standard, just reference to existing standards which aim to consider human health and comfort. The main criteria for suitable IAQ is that the indoor air poses low risk to health upon breathing and acceptable perceived comfort and human performance is achieved from the quality of the indoor air. The standard's objective is to identify methods for expressing quality of indoor air and its suitability for occupants with acceptable levels and guideline values for individual air pollutants. Although this standard applies to the design of new buildings, retrofit of existing buildings, commercial and institutional buildings and buildings with mechanical ventilation, parts of residential buildings that are similar to commercial and fit these categories are covered. The methods adopted for reduction or elimination of indoor air pollutants are source control (eliminating, modifying or substituting the source) and ventilation (improving ventilation effectiveness and using appropriate overall ventilation). Heating, ventilation and air-conditioning equipment should be correctly designed, installed and operated as these factors along with the state of maintenance can deteriorate the IAQ.

1.5 Carbon monoxide

1.5.1 Sources and occurrence of carbon monoxide

The main source of CO in the troposphere is accounted to unnaturally produced CO (El-Fadel and Abi-Esber, 2009). CO is the by-product of incomplete combustion of carbon based fuels and may arise in the home due to uses of such appliances as gas cookers and boilers. Increased levels of CO from combustion appliances may occur from improperly installed and maintained appliances, inadequate ventilation, blockages in flues and insufficient oxygen provided at the point of combustion.

Background CO concentration levels on a global average lie within 0.05 - 0.12 parts per million (ppm) but within urban areas this is usually a lot higher and variant depending on weather conditions as wind can be a factor in distribution

of air pollutants, traffic density and the time and distance from the sources. A typical 8 hour average of around 17 ppm, with peaks corresponding to rush hour traffic times can be observed in urban areas (WHO, Regional Office for Europe, 2000).

Other sources of CO include burning of wood and coal which can occur in the home for space heating. Tobacco smoking and incense sticks may be a source of indoor air pollution, where applicable, emitting CO and other pollutants. A study has shown how burning as few as two incense sticks in the home can lead to CO levels exceeding the WHO 1 hour guideline level for CO, with each incense stick producing as much as 557 mg of CO in comparison to 60 mg from a cigarette (Croxford and Kynigou, 2005).

Indoor concentrations of CO are not only affected by the indoor sources, but by the outdoor concentrations, proximity to outdoor sources, volume of the space and the mixing between indoor spaces (WHO, 1999). Indoor concentrations differ from home to home according to CO emission rate of an appliance, ventilation rate of the home and behaviour and activities of the occupants (Croxford *et al*., 2005).

During a power failure in New York, 264 people from 155 households were diagnosed with CO poisoning (Muscatiello *et al*., 2010). The main cause of exposure was portable generators, which attributed to three CO related deaths, and secondly were gas kitchen ranges. Although portable generators are useful for power outages, they would require 120 ach for levels acceptable set by the National Institute for Occupational Safety and Health. It is advised that generators are operated outdoors away from windows and doors. Half the homes had battery operated CO alarms, many reported that either the alarm did not sound or where it did no action was taken. It is possible that the potential to CO exposure from portable generators may increase from the effects of climate change, such as events of extreme weather, leading to power outages (Board on Population Health and Public Health Practice, 2011).

Compared to high-grade fuels, such as natural gas and biofuels, low-grade solid fuel such as those used to fuel small stoves and fireplaces can produce lethal amounts of CO if not ventilated correctly. The CO generated tends to dominate towards the end of the combustion cycle whereas PM dominates the pollutant generated at the start (WHO, Regional Office for Europe, 2010). Open-flued boilers were the main appliance reported by gas supply companies relating to incidents in the home between 1996 and 2004 (CORGI Trust, 2009). Emission rates were monitored for domestic cookers, finding considerably higher CO emissions in experiments where burners were using low flow rates (Wagner *et al*., 2010).

The Gas Safety Trust reviewed CO incidences between 1996 – 2010 involving piped natural gas in Great Britain, notably, it was observed that there was a decline in fatal and non-fatal incidences from 1996 to that of 2010 (Gas Safety Trust, 2011a). Those of 70 years of age or older were found to be five times more likely to be fatally injured in a CO incident. Central heating appliances (particularly those older than 21 years) and open flue systems were the most common reportable cause of CO incidents. Properties in densely populated areas such as Greater London and private landlord properties were more likely to have an incident occurring in them compared to owner occupied or social sector landlord. A significant proportion of faults recorded by investigators were related to ventilation.

1.5.2 Health effects of carbon monoxide

Carbon monoxide is a colourless, tasteless and odourless gas making it difficult to detect which could lead to accidental deaths or chronic health damage. The human route of exposure is via inhalation and CO poisoning affects both the physical and mental attributes of humans. Victims of high level exposure to CO have reported non-specific symptoms of headache, dizziness, tiredness, loss of balance, forgetfulness and nausea which can be misdiagnosed as these symptoms can be mistaken for other illnesses with the same symptoms such as influenza. CO is relatively unreactive in conditions found in the home and is not

absorbed by building materials or ventilation systems (WHO, Regional Office for Europe, 2010).

An indicator of CO poisoning can be multiple household members affected with symptoms that improve after leaving the area of exposure, and the time of year as CO poisoning is more common in winter due to the increased use of heating systems (Murphy, 2010). As CO has similar molecular weight to air, CO mixes freely with air and will move in air through bulk transport (WHO, Regional Office for Europe, 2010).In the UK, CO poisoning has claimed a greater number of deaths in children than any other type of poisoning (Communities and Local Government, 2008) and is the leading cause of accidental and intentional poisoning deaths (WHO, Regional Office for Europe, 2010). Misdiagnosis or length of time taken before testing occurs from leaving the area of CO poisoning may mean the CO levels have dropped, showing levels that do not cause concern. Of the recorded 562 deaths from CO poisoning from 1995 – 2009, approximately two out of three occurred in the home; gas from the mains supply and solid fuels were the main sources of CO identified (CO-Gas Safety, 2010).

A 2010 report by the Gas Safety Trust suggests that the use of CO alarms may be the explanation of why fewer fatalities were recorded in 2009/2010 than in 2008/2009. The number of incidents were reported to be similar but deaths and casualties were down as the alarms alert those in danger to a threat thereby reducing their exposure but not preventing the situation occurring (Gas Safety Trust, 2010). The period of highest risk where 84% of incidents occur is within the five months from November to March, where heating is most used. The report refers to a London Ambulance Service study of just five crews equipped with CO-oximeters, who were able to identify 83 cases which would have otherwise not have been detected, given that this was just five crews in London, if applicable nationwide the number of reported incidents of CO exposure would increase greatly. Post mortems in France include a mandatory CO test which can identify cases of CO related deaths, in the UK this is not the case so further cases may go unidentified. There was a continued reduction in incident numbers in 2010/2011 (Gas Safety Trust, 2011b) based on UK media reports;

there were 50 recorded incidents involving CO poisoning with 25 fatalities from 16 of these incidents - over three times as many fatalities to that reported in 2010. Although it was found that over 55s were most likely to own a CO alarm, half of the CO related incidents involving elderly people resulted in death.

CO poses health risks as it has a greater affinity for haemoglobin than oxygen. It inhibits the blood's ability to transport oxygen to the body by forming carboxyhaemoglobin (COHb), which has more than 200 times greater stability than oxyhaemoglobin (WHO, Regional Office for Europe, 1987). Approximately 80 – 90% of the exposed CO binds reversibly with the haemoglobin, COHb concentrations increase rapidly during exposure and begin to level off after 3 hours and within 6 – 8 hours reach a steady state (WHO, Regional Office for Europe, 2000). Measurement of COHb is often used as a marker for human exposure to CO (Green *et al*., 1999). Elimination of CO occurs through the lungs and typically has a half-life of 5 – 6 hours (WHO, Regional Office for Europe, 1987; Communities and Local Government, 2008).

Cardiovascular problems due to CO exposure are visible as the reduced ability to uptake oxygen has been shown to affect the ability of healthy young adults to exercise. The reduced oxygen uptake may therefore reduce productivity in some types of work or physical activity where exposure limits the activity. Chronic angina sufferers are found to be at high risk as well as those suffering from obstructed chronic arteries; even at lower levels of exposure of CO their situation is aggravated (WHO, Regional Office for Europe, 1987). CO compared to other major gaseous indoor air pollutants was found to be the strongest predictor of elderly patients being hospitalised for congestive heart failure (Bernstein *et al*., 2008).

A healthy person will have levels of COHb of 0.4 – 0.7% due to endogenous production of CO while the average levels in non-smokers, taking into account external routes of exposure, is of 0.5% – 1.5% (WHO, Regional Office for Europe, 2000). Non-smokers may have abnormally high levels due to occupational exposure, such as for delivery drivers and incidents where heavy exercise is undertaken in polluted environments (WHO, Regional Office for

Europe, 2000). Significant decrease in work time to exhaustion time in young healthy men exercising has been observed with COHb as low as 2.3 - 4.3%; smokers typically have levels of COHb of 3 – 4%, but heavy smokers may see levels to be as high as 10% (WHO, Regional Office for Europe, 1987).

CO induced hypoxia occurs with exposure resulting in poor functioning in some organs and tissues, such as the brain and heart which have high requirements for oxygen consumption. This can occur at concentration levels as low as 5% COHb (WHO, Regional Office for Europe, 2000). CO is also found to bind similarly to other haem proteins such as myoglobin found in muscle tissues which may have an adverse effect on cell function (U.S. EPA, 2000a). Below 10% COHb the effects are usually subtle, at concentrations of less than 20% COHb, lethargy, headaches and blurred vision are common symptoms (Murphy, 2010). Other health effects of exposure to CO include changes in fibrinolysis, decrease in blood pH and perinatal effects, including reduced birth weight and hindered postnatal development (WHO, Regional Office for Europe, 1987; Communities and Local Government, 2008).

At higher levels of exposure to CO the effects are greater and more obvious. Levels of 20% COHb typically carry symptoms of breathlessness on exertion and headaches, at 30% exposure severe headaches, weakness, dizziness, dimness of vision, disturbed judgment, nausea, vomiting, diarrhoea and increased pulse rate occur. Levels of 40 - 50% COHb can cause confusion, collapse on exertion, comas, and convulsions whereas at 60 - 70% levels of COHb leads to low blood pressure, slow pulse rates, respiratory failure and death (Communities and Local Government, 2008). Risk of health effects increase with duration of exposure, concentration of CO, altitude, vigorous activity, a high metabolic rate, age (foetuses, the young and the elderly), pregnancy and pre-existing illnesses (Crump *et al*., 2002).

According to the WHO air quality guidelines based on the Coburn-Foster-Kane exponential equation (Coburn *et al*., 1965), the recommended COHb levels, which are aimed at facilitating the requirements for non-smokers including special groups such as angina patients, pregnant women, the young and the

elderly, are 2.5 - 3.0% (WHO, Regional Office for Europe, 1987). Guideline values of time weighted average limits for concentrations in air are derived so that even during light exercise a normal subject, (non-smoker and not in a special group), should not exceed 2.5% COHb and it should not be exceeded or repeated within 8 hours (WHO, Regional Office for Europe, 2000). In 2010 the WHO released a 24 hour guideline to address long term exposure to CO, the guideline value for this is to not be exceeded when people are awake but excludes exercise (WHO, Regional Office for Europe, 2010):

100 mg m^{-3} (87 ppm) for 15 minutes

30 mg m^{-3} (26 ppm) for 1 hour

10 mg m^{-3} (9 ppm) for 8 hours

7 mg m^{-3} (6 ppm) for 24 hours.

(At 1 atm & 25 ℃, 1 mg m^{-3} = 0.873 ppm)

A 30 minute guideline of 60 mg m^{-3} (52 ppm) is not included in the 2010 WHO guidelines but was included in previous guidelines (WHO, Regional Office for Europe, 2000).

Chronic effects of CO exposure can occur as the after effects of acute poisoning which may have caused irreversible damage to the casualty's neurological and psychiatric wellbeing. Prolonged or repeat exposure to low concentrations of CO can have a chronic effect, but may be overlooked with similar symptoms to common illnesses, risking re-exposure, leading to deterioration in work/educational performance (Communities and Local Government, 2008). Treatment for CO poisoning is carried out with normobaric or hyperbaric oxygen, which speeds up the elimination of CO as the oxygen competes with CO at haemoglobin binding sites (Murphy, 2010). Acute CO poisoning can cause severe hypoxia with short term reversible effects and patients may also appear fully recovered only to later express delayed

neurological damage in subsequent weeks even after treatment (Mehta *et al*., 2007).

1.5.3 Methods of measuring carbon monoxide in air

There are various methods available for measuring CO with types of devices and specifications given in various relevant standards. Other sources of information about available monitors include published studies of indoor air quality and exposure as well as manufacturer's literature about CO measuring equipment. British, European and International standards for measuring CO in ambient air and from combustion appliance emissions are summarised in Appendix B.

1.5.4 Electrochemical sensors

CO electrochemical gas sensors generate a current proportional to that of the CO gas in the surrounding atmosphere. The current is generated via electrochemical oxidation in an aqueous solution, by the reaction of CO to CO_2 (Equations 1-1 – 1-3). The electrochemical cell typically comprises of three electrodes; a working electrode where the oxidation (or reduction) of the target gas occurs, a counter electrode which chemically balances the reaction of the working electrode and a reference electrode which maintains a constant potential at the working electrode to ensure a constant sensitivity is maintained. The cell electrolyte, typically sulphuric acid, provides an ionic pathway between the electrodes.

Equation 1-1: Reaction on working electrode:

$$CO + H_2O \rightarrow CO_2 + 2H^+ + 2e^-$$

Equation 1-2: Reaction on counter electrode

$$½O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

Equation 1-3: Overall reaction

$$CO + ½O_2 \rightarrow CO_2$$

This oxidation of CO occurs on the working electrode surface, an electro catalytically active noble metal. When the CO gas comes into contact with the sensor, it passes through a thin membrane to reach the surface of the electrode. The rate of diffusion through the membrane controls the concentration of CO reaching the electrode and is dependent on the CO concentration in the atmosphere under analysis (U.S. EPA, 1991). The counter electrode reacts with O_2 from the air to generate water.

Electrochemical sensors offer a versatile tool for field sampling with portable units widely available, interference from other gases can occur with the main interfering gases for CO electrochemical sensors being acetylene, ethylene, hydrogen, ammonia, hydrogen sulphide, nitric oxide, nitrogen dioxide and sulphur dioxide (U.S. EPA, 1991). This can be reduced by the use of filters to limit or remove interfering gases by chemically absorbing or catalytically reacting with the interfering gas (Alphasense, 2010).

Many studies have used electrochemical sensors for determining the CO concentration in air as sensors can provide continuous monitoring, with units available that can monitor not only CO but also humidity, temperature and CO_2 as used in a study on IAQ in immigrant homes in the USA (Miller *et al*., 2009). Portability and cost can be an important factor in its preference to other monitoring devices, previous studies have seen the device used for various methodologies including recording data whilst in transport or commuting (Chan and Liu, 2001; Chan *et al*., 2002; Duci *et al*., 2003), evaluating IAQ and pollution (Ryhl-Svendsen *et al*., 2010; Clark *et al*., 2010) and personal exposure levels in various situations (Georgoulis *et al*., 2002; Kim and Wagner, 2010).

An advantage of this technique is that modern equipment can be very sensitive with specific filtering of the major interfering gases, as well as small and easy to power and providing continuous analysis, unlike other techniques which may require air samples to be gathered prior to further analysis (El-Fadel and Abi-Esber, 2009).

Croxford and Fairbrother (2005) describe the use and accuracy of an indoor electrochemical CO monitor which is reported to be economical, small, lightweight and rechargeable. They refer to the cost of a non-dispersive infrared (NDIR) monitor, which was previously thought to be the only approved method, as too expensive, too large and too power demanding. The unit described (ICOM), is completely silent, unobtrusive, self-contained, with simple operation. There is no digital display hence no real time data can be obtained at time of use, as it was designed to log in dwellings and they did not want to alert occupants to concentration levels, which could potentially result in them altering their behaviour and thereby invalidating the results. Also no ethical consequences can arise from this as the CO levels are unknown at the time of measurement. Accurate measurements at low ambient levels of CO can be achieved with accuracy to ±0.2 ppm and readings from co-exposed units were very similar (Croxford and Fairbrother, 2005). The ICOM has been used in previous studies of unattended home monitoring (Croxford *et al*., 2005; Croxford *et al*., 2006; Milner *et al*., 2006).

1.5.5 Gas chromatography

Determination of CO via gas chromatography (GC) can be undertaken in conjunction with various types of detectors, commonly flame ionisation is used. High volume air samplers can be used to collect the air sample to be inserted in the chromatograph. When an air sample containing CO is injected into the column, the gas is dried, pre-concentrated, reduced to methane and the flame ionisation detector then records the eluted product (U.S. EPA, 2000a).

An advantage of this method is that there are no known interferences as the CO is separated from water, CO_2 and hydrocarbons other than methane by a stripper column. An analytical column then separates CO and methane, which if present is eluted first, passing straight through a catalytic reduction tube. When CO passes through this tube, it is reduced to methane before passing to the flame ionisation detector, with this signal proportional to the concentration of CO in the sample. GC can be used to measure levels from 0.02 – 45 ppm with an

uncertainty of ±10% and is the preferred method for analysis of low COHb levels in blood occurring from ambient exposure to CO (U.S. EPA, 2000a).

In a 2005 study looking into the human health effects of exposure to pollutants in urban air (Ghose *et al*., 2005), air was collected by high volume air samplers and samples drawn with a syringe to be injected into the gas chromatograph. Samples of air were collected two days a week in three 4 hour shifts, so samples collected would give just an average CO concentration of the time shift and specific peak time concentrations would not be identified.

Various detectors can be used in conjunction with GC, including electrochemical detectors where the CO gas is first separated from a mixture of gases in the column before coming into contact with the electrochemical detector and the elution time can be recorded against the outputted voltage.

1.5.6 Infrared analysers

CO is an infrared active gas, where its absorption of infrared radiation is proportional to its concentration. NDIR analysis can be used to measure the concentration of CO in the presence of other gas as the absorption is unique to CO, near 4.6 μm and can therefore be distinguished.

It is thought to be the most reliable method and is the most used analyser for fixed site monitoring stations measuring CO in ambient air continuously and is widely adopted (U.S. EPA, 2000a; British Standards Institution, 2005a; California Air Resources Board, 1999), as NDIR methods are sensitive over a wide range of concentrations, have short response time, require no wet chemicals, are relatively insensitive to flow rate and have a reasonable independence of changes in temperature (U.S. EPA, 2000a; El-Fadel and Abi-Esber, 2009).

Interfering gases, such as CO_2 and water vapour, can be removed by filters and desiccants and measurement is very specific to CO. High sensitivity can be achieved with detection limits observed of 0.005 ppm and with a resolution of 0.001 ppm (U.S. EPA, 2000a). Generally these units are set up for analysis at

stationary monitoring stations with portable units available, but are expensive and require a larger power supply in comparison to that of electrochemical sensors.

1.5.7 Colorimetric indicators

There are many variants to these types of method, such as the length of stain indicator tube, which measures the length of stain in relation to concentration and colorimetric indicator tubes, which measures the intensity of colourisation in relation to concentration. An example is the Dräger tube using the reaction of diiodine pentoxide with CO under acidic conditions producing CO_2 and molecular iodine, the colour which stains the tube proportionally to the mass of the CO (WHO, 1999). A concentration gradient created between the surrounding air and the tube drives the movement of the reaction up the tube. At the end of the exposure period, the coloured stain is read against markings of parts per million per hour (ppm h^{-1}) on the tube, dividing this value by the length of time of exposure to the air under analysis will give the time weighted average concentration in ppm over a period of time, peak concentrations cannot be obtained (Dräger, 2008). Dräger indicator tubes are a passive diffusive method that can be used for personal monitoring by attaching to clothing.

These methods are not recommended for accurate readings of CO, but more for indication of levels (U.S. EPA, 1991), as interfering gases also affect the readings of these methods. Indicator tubes are cheap and suitable for the analysis of highly polluted air (WHO, 1999), but the accuracy for these methods are estimated to be ±25% (U.S. EPA, 1991) and its use is generally limited to giving qualitative results only (El-Fadel and Abi-Esber, 2009). Limitations to the tubes include that they can only be used once. The length of colourisation is subjective; judgement may be difficult as the colouring may be slanted where an average has to be taken or may become progressively diffuse, making it difficult to evaluate the end of the colourisation (Dräger, 2008).

Passive diffusion tubes are intended to measure relatively high concentrations for a sampling period of a few hours. Nash and Leith (2010) investigated their

use for measuring much lower concentrations for periods of up to a week in a laboratory setting. For CO diffusion tubes, a gas cylinder of CO was diluted with a clean airflow to generate concentrations of 0.60, 1.55, 4.14 and 7.54 ppm. Three CO colorimetric diffusion tubes were placed into a chamber of 0.028 m^3 for each concentration and the length of stain was monitored on multiple occasions throughout the week exposure. Low concentrations for CO matched well but concentrations measured near the lower detection limit tended to be imprecise. The authors concluded that the findings suggest that colorimetric tubes can measure low concentrations over extended periods reasonably well. Although not as accurate or precise as real time monitoring instruments they can be of use where cost, size, noise and electrical supply are concerns.

1.6 Appropriate strategies for CO measurement

A British Standard method for indoor air sampling that describes approaches such as monitor location along with measurement methods is described below. Parallel information should be recorded in conjunction with CO and other pollutants measured, such as an activity diary, to correlate with peaks in indoor air pollution and to identify possible sources of exposure.

1.6.1 BS EN ISO 16000

The ISO 16000 series looks at indoor air measurements for various indoor environments including dwellings, public buildings and offices. The intended use for part 1 (British Standards Institution, 2006), is for aiding the planning of indoor air pollution measurements. Other parts in the series describe specific strategies for sampling for particular or groups of substances. It is emphasised that an inappropriate monitoring strategy can contribute to the overall uncertainty of the measurement.

It is recommended that the WHO guidelines are referred to when interpreting if the indoor air measurements are satisfactory. The location of sampling should account for spatial variation and in private dwellings should not affect the use or occupant behaviour. The centre of the room is considered to be the most

suitable location but if this is not acceptable, the monitor should be no closer than 1 m to any wall and about 1 - 1.5 m above the floor. The equipment should be protected from human intervention and areas the samplers should not be placed are in the sun, near a heating system and near draught or ventilation sources. Further detail of the standard is provided in Appendix B.

1.6.2 Other strategies

Concentrations of CO in an enclosed environment are affected by factors that need to be taken into account when sampling, such as the source, outdoor concentrations, proximity to outdoor sources, volume of space, mixing and ventilation (WHO, 1999).

A study looking at gas cooking, ventilation and exposure to combustion products ensured that the sensor was placed between 0.5 - 3.0 m from the stove on top of an open surface, at a height of 1.0 - 1.5 m (the breathing zone) and not directly in the flow of air (Willers *et al*., 2006).

Monitoring of occupant exposure to CO in a study of the home environment deemed the ideal monitoring position to be the head height of a seated individual, in a representative position in the living area and the data logger used was placed as far from sources of CO and draughts as possible and out of direct sunlight (Croxford *et al*., 2005). Efforts to ensure that the data collected was representative of occupant exposure were balanced with the need for the logger's position to be acceptable to the occupants.

Personal exposure monitors have been previously used where measurements are obtained from the use of monitors attached to the participants of the studies as opposed to monitoring at stationary fixed positions, such as in a kitchen or bedroom. This can be advantageous for looking at exposure of pollutants at a personal level throughout a home or other microenvironments, but a disadvantage lies in the participants having to have the monitor with them throughout the duration of the study.

Lai *et al*., (2004) monitored personal exposure over 48 hours in a study where the participants carried monitors for measuring PM, VOCs, CO and NO_2. Microenvironmental exposure was also observed with stationary monitoring carried out indoors and outside of the participant's homes and also inside their work place. In a study monitoring NO_2, passive tubes were located in the kitchen, living room and a bedroom in locations selected to avoid window openings, corners of rooms and heating ventilation (Kornartit *et al*., 2010).

Personal exposure to CO across 5 European cities has been observed over 48 hours in conjunction with an activity diary and questionnaire to provide a detailed record of their activities. Ambient CO levels were also recorded at fixed site stations (Georgoulis *et al*., 2002). The questionnaire detailed information on the home and work environment, commuting and activities. The activity diary detailed the microenvironment and activities such as cooking, active or passive smoking, time spent in transport, type of transportation, and time spent indoors and outdoors.

The BS 7967 standard series for monitoring CO in dwellings (British Standards Institution, 2005c), has strategies for gas operatives in conducting emissions testing with different methods for different appliances and only one appliance is operated at a time. This strategy is not very useful for monitoring occupant's exposure on an everyday occurrence with their natural behaviour but more of a means for testing of gas appliance compliance with emissions.

Key points for assessing indoor air summarised from "A protocol for the assessment of indoor air quality in homes and office buildings" (Crump *et al*., 2002), are that the appropriate sampling position is at breathing height (1 – 2 m) in a central location that would not hinder occupant activity, sampler locations should not be located in positions where a single source will affect readings or by incomplete mixing of air. Living rooms and bedrooms should be sampled as occupants will spend the majority of their time there and at least one parallel outdoor measurement should be taken.

1.6.3 Concentrations in indoor air

Fixed site monitors are used to measure ambient air with which a population will come into contact when outdoors, but these alone are not accurate in estimating exposure as approximately 90% of people's time is spent indoors (WHO, 1999). Outdoor levels of CO are related to indoor levels, as outdoor sources will gain access via infiltration, ventilation and by mixing of air. Indoor levels can be much higher than those observed outdoors due to appliances used and their emission rate, ventilation rate and behaviour of occupants (Croxford *et al*., 2005). Indoor levels are expected to be higher in homes within a close proximity to outdoor sources, such as industry, busy roads and in housing with attached garages which are used for parking motor vehicles.

For UK homes, there is not much literature available about CO levels in energy efficient homes. A Department of Health report refers to a study in the mid-eighties with a large CO range of 0 – 42 ppm where the concentration peaks in houses correlated with the use of combustion appliances and considers that a decrease in levels of CO in the home occurred in the mid-nineties with levels below 3 ppm observed in a couple of studies (Department of Health, Committee on the Medical Effects of Air Pollutants, 2004).

CO monitored in winter over 14 days in 37 new English homes using passive Dräger tubes observed geometrical means of 0.12 ppm in the living room and 0.16 ppm in kitchens (Crump *et al*., 2005). Five of these were continuously monitored and peak concentrations in the kitchen of 27.9 ppm for a 1 hour average was observed, which occurred during gas cooking.

In a study of 56 UK homes studied during the winter of 2002/2003, electrochemical CO monitors were placed in a representative location in the living room taking the 15 minute average of minutely recorded values (Croxford *et al*., 2005). A mean level of 1.9 ppm CO was monitored for all homes, but 13 of these 56 homes had CO levels that exceeded the WHO guidelines. Further investigation of these 13 to assess the source was carried out by a gas engineer and two of the 13 operated faulty appliances emitting in excess of

1000 ppm of CO. Croxford *et al.,* (2006), measured CO emissions in the living room of 270 homes with CO monitors installed away from direct sources of CO, sources of cleaner air and ventilation, out of direct sunlight and were as close as possible to the head height of a seated individual. Out of the 270 homes, 50 exceeded the 8 hour WHO guideline of 9 ppm, 10 of these also exceeded the 30 minute guideline of 52 ppm. Findings for both of these studies where the homes under observation were all owner-occupied, low income households and had at least one gas appliance, were that CO guidelines were exceeded due to poorly maintained and installed appliances with the most common problem appliances found to be gas powered grills or fires (Croxford, 2007).

Emissions from gas appliances in 597 UK homes were checked by gas engineers, with 20% having a poor quality or dangerous appliance exceeding the recommended levels CO levels (Croxford, 2007). The author acknowledges the sample is biased and therefore unrepresentative of the UK, as a large sample of the houses were from one area, the type of houses were mainly terrace with flats and detached housing largely unrepresented, residents were mainly elderly and a large proportion were claimants of social welfare.

Gas cooking, tobacco smoking and flueless appliances for heating have shown to significantly increase CO levels in 830 UK homes (Raw *et al*., 2004). Averages over 14 days were taken using Dräger colorimetric indicator diffusion tubes in kitchens and bedrooms with levels of 0.41 ppm and 0.34 ppm respectively found, and a maximum level of 3.4 ppm was observed. Concentrations were found to be significantly higher in kitchens to that of bedrooms and main indoor significant determinants of CO were gas cooking, tobacco smoking and flueless combustion appliances. It was also found that rural areas had lower CO levels than more densely populated areas, suggesting outdoor CO is impacting in the urban areas and seasonal effects are observed with an average of 0.9 ppm found in the winter compared to 0.4 ppm in the summer in kitchens with gas cooking.

Henderson *et al.,* (2006) looked into short term CO peaks in homes of the elderly in Wales by types of household fuels in smoking and non-smoking

households using electrochemical sensors to monitor the living room. In both smoking and non-smoking households LPG fuel had the highest peak (53.6 ppm and 22 ppm for smoking and non-smoking respectively), and average CO concentrations observed in the study (6.1 ppm and 0.5 ppm for smoking and non-smoking respectively). Gas fuel in smoking households observed a maximum peak of 45.7 ppm whilst in non-smoking households a maximum peak of 17 ppm was observed for gas fuelled households.

A study of London offices found CO levels did not exceed a 15 minute average of 4 ppm and assumed the majority of CO within the building had occurred due to outdoor sources (Milner *et al*., 2006). Electrochemical sensors were used in the monitoring of CO and indoor concentrations were monitored using the previously described ICOM. The CO levels on the same floor were also found to be greater when closer to a busy road, lower floors had greater levels of CO and there was no significant variation in CO in different parts of the same room.

Personal exposure CO monitoring using electrochemical sensors was performed in Oxford involving 50 adults, where a geometrical average of 0.34 ppm for 48 hours was observed, with peak levels observed during activities of smoking, cooking and transportation (Lai *et al*., 2004).

A paper suggesting neurological symptoms are linked to low level exposure to CO (Croxford *et al*., 2008), used self-reported surveys and measured CO released from the gas appliances in the houses with electrochemical flue gas analysers. The houses were mainly in old, urban areas of London and some emissions exceeded 1000 ppm for open flue boilers and exceeded 100 ppm for gas fire and boiler spillages and were over 200 ppm for cooker emissions.

Oreszczyn *et al.,* (1998) looked at changes in the UK Building Regulations and the possible effects on removal of pollutants. Homes were observed for at least three weeks in the two winters over 1996 – 1998. Measurements of CO, NO_2, temperature, relative humidity and dust mites were recorded in 45 occupied homes built since the change in the Building Regulations all of which had gas cookers and 39% were smoking households. None of the homes exceeded

guidelines for CO and observed peaks were associated with cooking. Smoking households had levels over 50% higher than non- smoking homes. Homes where trickle ventilators were open observed lower mean CO levels (trickle ventilators are controllable flaps incorporated within the frame of a window that can be opened to allow ventilation of air without opening the window).

A report summarising a study looking at combustion products emitted from a range of flueless gas appliances at varying firing rates measured in a 48 m^3 sealed chamber with varied ventilation concluded that poor combustion resulting from lower burning rates and the interaction of flames playing directly onto surfaces, such as grills and pans, was found to increase the amount of CO produced, as well as ultrafine particles (UFP) and formaldehyde (Upton *et al*., 2004). CO was found to reach a maximum of 48 ppm with conditions of 1 ach on a low burning flame for a flueless gas stove.

Kitchens are found to have elevated levels of air pollutants including CO, due to the location of intermittent sources of combustion. A Dutch study (Willers *et al*., 2006) found a weekly average of 0.4 ppm with a maximum of 5.2 ppm of CO and compared its results with an older Dutch study (Lebret, 1985) which made measurements in several rooms and found kitchens to have the highest levels. The homes Lebret observed had a weekly average of 1.7 ppm in both rural post-war homes and urban pre-war homes. Willers *et al.,* conclude that the newer homes studied in the later study appear to have lower weekly average CO concentrations, suggesting changes in the modern home has reduced levels of CO, which may be due to more efficient appliances, better maintained appliances and/or greater air supply and ventilation rate.

The California Air Resource Board continuously monitored CO and other combustion products during various cooking activities and with various cooking appliances; a gas cooker, an electric cooker and a microwave (Fortmann *et al*., 2001). Testing was performed in a single home built in 1983 and the CO was monitored in the kitchen, living room and master bedroom using NDIR. The study aimed to characterise emission rates and observe exposure to pollutants generated from cooking. It was found that monitored outdoor CO ranged from

0.1 – 1.1 ppm and indoor CO ranged from 0.4 – 20 ppm. The highest observed CO concentration was observed during the self-cleaning test of the gas oven when the 5 hour average for CO in all the indoor monitored rooms during this was 14 ppm. The second highest concentration of CO was observed during the electric oven self-cleaning test. This could be due to the high temperature used to clean the oven in the self-cleaning cycle burning of food residues. CO concentrations during cooking were generally below 4 ppm and exceeded 9 ppm in the test with gas where there was preparation of a full meal and broiling of fish, the latter had the highest peak for cooking activities of 11.4 ppm. The indoor CO for cooking activities averaged between 1 – 5 ppm, the authors note that although below the recommended 8 hour average guideline of 9 ppm, this could contribute to elevated levels in combination with other indoor and outdoor pollutant sources that could affect human health.

Monitoring of CO in two retirement homes in Los Angeles was undertaken where measurements were taken indoors and outdoors (Polidori *et al*., 2007). One of the homes was situated away from a source of local traffic but by a construction site and the other home was in close proximity to a freeway. The study took place over two different phases; in summer and in winter for both the homes, CO was monitored using IR analysers. 0.98 ppm was the highest average for indoor measurements of CO which was observed in the retirement home located near a freeway in the winter period; this was also the same location and period for the highest average outdoor measurement of 0.81 ppm.

Real time measurements of CO were carried out in 108 new Californian homes using a TSI IAQ-Calc meter fitted on a tripod connected to an AC power outlet monitoring the living room of the property (Offermann, 2009). Monitoring was performed for approximately 24 hours and occupant activity was detailed in an activity diary for a 48 hour period which included the 24 hours of monitoring. Parallel outdoor concentrations were also recorded. The study was conducted over multiple seasons, 1 hour averages from the monitored CO ranged from 0.4 – 4.4 ppm for indoor CO and 0.4 – 4.9 ppm for outdoor CO.

CO among other gases was monitored for three to four days in 30 American homes with unvented gas heaters advertised to be 99% efficient (Francisco *et al*., 2010). CO was monitored with an NDIR approximately 2 metres from the heater and recording CO at 1 minute intervals. It was found that CO exceeded the 8 hour average of 9 ppm in 20% of the sample. CO distribution analysis showed that CO disperses throughout the home and up to 80% of the level near the heater was monitored in various locations with portable CO monitors. The highest 8 hour average monitored from the sample homes was 14 ppm.

Controlled short term release of CO and sulphur hexafluoride in 3 residential homes was monitored, with CO continuously monitored electrochemically, to observe the effects of the internal doors on the transport of air pollutants (Ferro *et al*., 2009). Results found that closing internal doors in the room of the source effectively prevented transport of CO to another room which was monitored in the house, with efficiency close to 100%. Partially opened doors can facilitate the transport of air pollutants throughout the house, even when only opened a few centimetres. The distance between the rooms also affects the transport.

A US study looking into CO and other combustion pollutants emitted from five types of portable combustion appliances used an electrochemical logger with a detection limit of 0.4 ppm recording the 1 minute averages for CO (Fan and Zhang, 2001). Investigation of a kerosene lamp, oil lamp, candles, kerosene space heater and portable gas range found highest CO levels to be associated with the kerosene lamp, ranging from 9 – 20 ppm and the highest emission rate was from the kerosene space heater at 226.7 ± 100 mg h^{-1}.

The effect the proximity of a source has on monitored exposure was explored in a study investigating the reported discrepancies between stationary indoor monitors and personal exposure monitors (McBride *et al*., 1999). Space-time variation and the proximity effect of CO emitted from a pure CO gas cylinder was studied in the living room of a Californian home and continuously monitored with 11 electrochemical sensors at various locations throughout the room from 0.25 – 2.0 m from the source with various heights and angles and with one stationary monitor 5.4 m from the source. The study observed an evident

proximity effect along one or more angles of the various heights and distances of monitoring locations throughout the room with relation to the source. The 11 monitors in close proximity to the source observed higher and more variable CO concentrations. Monitors at a 45° angle and less than 0.5 m away from the source were found to record the highest CO concentrations, with levels typically 3 times that of the stationary monitor. Monitors at a 270° showed less evidence of a proximity effect.

1.7 Other combustion gases

1.7.1 Nitrogen dioxide

NO_2 is a reddish-brown gas produced in combustion processes by a two-step reaction of nitrogen and oxygen to form nitric oxide (NO) where further oxidation can occur over time to form NO_2. This exothermic reaction is promoted by the cooling of combustion exhaust gases (British Standards Institution, 2008b). Concentrations of NO_2 from emissions and ambient air will differ from sources, activities, environmental occupation, room type and over time (British Standards Institution, 2008b). NO is produced naturally in human lungs and is harmless at moderate concentration, but NO_2 is of interest with regard to IAQ as this water soluble gas is also an irritant and a strong oxidant (WHO, Regional Office for Europe, 1987).

Where NO_2 is found NO is also found, collectively known as oxides of nitrogen, NO_X, which can also occur naturally due to soil and plant activity. NO_2 is the most toxic of NO_x, at high concentrations NO_2 can cause severe and fatal lung damage, causing inflammation of the airway (Department of the Environment, 1996). Asthma sufferers seem to be worst affected by exposure and effects on health can be acute and chronic and the oxidising properties of NO_2 damage cell membranes and proteins. Female adults and atopic allergy sufferers are also suggested to be more sensitive to NO_2 exposure (Bernstein *et al*., 2008).

Levels of NO_2 found in homes are unlikely to cause serious acute effects but could aggravate the effects of allergens in asthmatics leading to hospitalisation

and even death (Crump *et al*., 2002). The majority of atmospheric NO_2 is emitted as NO where rapid oxidation by ozone occurs to form NO_2. Hydrocarbons reacting with NO_2 in a photochemical reaction in the presence of ultraviolet (UV) light are a major source of tropospheric ozone and nitrate aerosols PM in ambient air (WHO, 2006).

On a global atmospheric scale, background levels of NO_2 are very low. Naturally produced NO_X through bacterial activity, volcanic activity and lightning action outweigh those produced by human activity where the greatest emissions come from the combustion of fossil fuels. Indoor sources include tobacco smoke, use of gas appliances and oil stoves; if not effectively vented or flued these emissions may exceed those found outdoors which are mainly owing to vehicle emissions (WHO, Regional Office for Europe, 1987).

Wilson *et al*., (2006) found that homes built after 1995 observed lower indoor NO_2 concentrations than older homes monitored despite an increase in building air tightness. The monitoring took place over the winter of 2005/2006 and was a follow up to a 1985 study; on average a 50% reduction in NO_2 levels was observed in the later study.

Levels of NO_2 in the home are low in relation to concentrations found to be toxic and there are no specific symptoms associated with low level exposure. Animal and human studies indicate that short term exposure to 200 µg m^{-3} has significant health effects (WHO, 2006). There is insufficient evidence for setting a guideline concentration for NO and the guidelines for NO_2 recommended by the WHO to protect human health are: 40 µg m^{-3} annual mean, 200 µg m^{-3} 1-hour mean (WHO, 2010), where1 µg m^{-3} = 5.32 x10^{-4} ppm.

Guideline values for 1 hour exposure levels for NO_2 are based on studies showing increased bronchial responsiveness at levels of 200 µg m^{-3} although the lowest level of NO_2 exposure to show a direct effect on pulmonary function is 560 µg m^{-3} (WHO, 2006). Other studies of asthmatics have failed to find any effect of NO_2 at concentrations up to 5600 µg m^{-3}, suggesting some asthma

sufferers are more susceptible than others (Communities and Local Government, 2008).

Toxicological studies of NO_2 are usually unrepresentative of levels that occur in dwellings. Animal studies have shown how on exposure reduced capability for defence mechanisms of the lungs can increase infection vulnerability, where concentration is thought to be a greater factor rather than length of exposure (WHO, Regional Office for Europe, 1987; Communities and Local Government, 2008). Other animal studies have failed to show that low concentration exposure to NO_2 has adverse health effects, but prolonged exposure can cause lung damage (Burr, 2001).

Indoor concentrations are expected to increase with the increasing number of gas appliances in the home. Gilbert *et al.,* (2006) diffusively monitored indoor concentrations of NO_2 in Canadian homes and observed significantly elevated concentrations in homes equipped with gas stoves and to a lesser extent with gas heating. Lee *et al.,* (1995) also found American homes with gas stoves and pilot lights to have NO_2 levels higher than that of homes with electric stoves. An international study on 15 countries found that use of a gas stove in the home was the principal factor influencing indoor NO_2 concentrations, suggesting the relationship between gas appliances and increased indoor NO_2 is not dependent on countries (Levy, 1998).

NO_2 concentrations were monitored in 360 Spanish homes with one year old children (Esplugues *et al*., 2010). It was observed that homes with gas cooking appliances, gas fuelled water heaters, homes without central heating and homes where extract ventilation was not used whilst cooking were found to have higher NO_2 concentrations. The greater urbanisation of the surrounding area to the home was also associated with increased NO_2 levels. Similar findings were observed in a 1997 Danish study of 103 children living in an urban area and 101 children living in a rural area which monitored NO_2 outside the front door, in the child's bedroom and on each child using diffusive badges (Raaschou-Nielsen *et al*., 1997). Factors found affecting personal NO_2 exposure included outdoor concentrations and use of gas appliances in the

home. Passive smoking, being near an open fire and burning of candles were also found to increase personal exposure levels indoors.

A study into NO_X generated by gas and electric cooking (Dennekamp *et al*., 2001) found that highly elevated concentrations of NO_X may be generated by gas combustion with no extract ventilation and poor general ventilation, with concentrations reaching amounts which may cause adverse health effects. Five minute peaks of approximately 1880 µg m^{-3} NO_2 were observed with cooking on four gas rings for 15 minutes.

In a cooking study observing NO_2 among other combustion products and air pollutants during various cooking methods and with gas and electric appliances in a single home, it was observed that during self-cleaning of a gas oven a 5 hour average of 756 µg m^{-3} was monitored using a chemiluminescence monitor (Fortmann *et al*., 2001). Nitrogen dioxide levels increased during cooking activities with a gas stove and the highest levels of NO_2 were observed during cooking fried chicken which produced an average indoor level in the kitchen, master bedroom and living room of up to 756 µg m^{-3}.

A UK study measure personal exposure and microenvironment exposure of indoor and outdoor NO_2 involved 60 subjects in winter and 30 subjects in summer using passive diffusive Palmes tubes (Kornartit *et al*., 2010). Results found that during the winter monitoring, concentrations in homes with gas cooking were significantly higher in all rooms of the house; kitchens with gas cookers were on average twice as high as those with electric cookers. The subjects were selected by profiling of 21 – 60 year old office workers in urban areas. Tubes were located on the participant, in their bedroom, living room, kitchen, front of property, office and car with weekly NO_2 averages recorded. Average personal exposure in winter ranged from 10.9 to 21.1 µg m^{-3} (21.6 to 29.3 µg m^{-3} in summer) for subjects with electric cookers and 12.1 to 29.5 µg m^{-3} (24.3 to 34.6 µg m^{-3} in summer) for subjects using gas cookers. The highest difference observed between homes with gas cookers and homes with electric cookers was in the kitchens, where gas cooking homes ranged from 24.7 to 74.3 µg m^{-3} (24.5 to 33.9 µg m^{-3} in summer) compared to 8.0 – 18.6 µg m^{-3}

(15.3 to 25.5 μg m^{-3} in summer) in electric cooker homes. In summer it was found that the difference between rooms was lower than in the winter period. Smokers, and to a further extent smokers with gas cookers, had higher personal exposure than non-smokers and passive smokers. The study also concluded that outdoor NO_2 could be a key source of indoor NO_2 in homes without gas cookers.

In the spring of 1996, NO_2 was measured over 6 days in the living rooms of 119 Californian homes using diffusive sampling badges with outdoor samplers also used at each house (Lee *et al*., 2002). Average indoor concentrations were 38 μg m^{-3} and average outdoor concentrations were 53 μg m^{-3}, indoor levels were higher in homes with air conditioning and gas appliances. Homes were either located in a valley site or a mountain site, with those in the mountain site having lower concentrations of indoor and outdoor NO_2 suggesting a geographical influence on the levels of NO_2 observed. Exposure to NO_2 in a sample of pregnant women in Spain was monitored for 48 hours with outdoor, indoor and personal diffusive samplers (Valero *et al*., 2009). Personal exposure to NO_2 was influenced greatly by indoor concentrations, where the indoor concentration levels were significantly influenced by outdoor concentrations of NO_2 and the use of gas cookers.

Gas appliances have also been associated with increased respiratory symptoms, where reduction in lung function in a study of 125 asthmatics wearing diffusive sampling badges at home over 6 weeks was observed with certain types of gas appliances associated with greater personal exposure to NO_2 (Smith *et al*., 2000). Higher indoor NO_2 concentrations were also associated with increased asthma symptoms in an American study of 150 inner city children diagnosed with asthma. Monitoring NO_2 in the child's bedroom for 72 hours was undertaken using a diffusive sampler; gas stoves in the home and the use of a gas appliance for space heating were associated with higher NO_2 concentrations (Hansel *et al*., 2008).

An American study of unvented gas heaters observed that in the 30 homes sampled NO_2 was the combustion product that most frequently exceeded health

based guidelines (Francisco *et al*., 2010). The WHO 1 hour average guideline was exceeded in 80% of the homes, irrespective of the usage patterns, unlike CO which exceeded guidelines when use was inconsistent with recommendations. Unlike CO, NO_2 has additional mechanisms of removal, such as chemical reactions to interior surfaces and furnishing.

A Communities and Local Government report on ventilation and IAQ in homes built in compliance with 2006 Building Regulations observed that four out of the 22 dwellings monitored had levels of NO_2 that exceeded the recommended 40 µg m^{-3} long term average given in AD F (McKay *et al*., 2010). The mean concentration of all dwellings monitored was 24 µg m^{-3} and for the 14 dwellings that just used gas for cooking the mean was 29 µg m^{-3}. In the four homes that the recommended levels were exceeded, it was thought that this was due to extract ventilation not being used or being incorrectly installed.

1.7.2 Methods of measuring nitrogen dioxide

As with CO, methods for measuring NO_2 are described in standards (Appendix B) relating to indoor air measurements of NO_2, as well as in published studies and in literature about measuring instruments.

1.7.3 Diffusive nitrogen dioxide samplers

The Palmes tube is a widely used passive diffusive sampler which works by the diffusive transport of NO_2 to a net (commonly stainless steel, although glass fibre and cellulose filters have been previously used), coated in triethanolamine at the sealed end of the tube (British Standards Institution, 2008b; Palmes *et al*., 1976). The open end of the tube is exposed to the air to be tested. The nets are extracted by solvent and determination of the nitrate ions, formed by reaction of NO_2 with the chemicals on the net, can be achieved photometrically. Interferences to the methods are nitrous acid and peroxy acetyl nitrate which could increase the levels reported for NO_2. Lower detection limits occur on greater length of exposure, with typical limits for a 24 hour period of 28 µg m^{-3} and after an exposure of one week 4 µg m^{-3}. The principles for Palmes tubes

are the basis for other diffusive samplers, such as sampling badges also using triethanolamine aimed at personal exposure studies: ion chromatography is often used for analysis.

Direct reading colorimetric detector tubes, such as the Dräger tubes as described earlier in relation to CO measurements are also available for NO_2. In NO_2 Dräger tubes the reaction of NO_2 with diphenylbenzidine or ortho-tolidine is monitored by a colour change and the concentration is measured against the length of stain on the tube. Interfering gases are chlorine and ozone, NO does not affect the reading (Dräger, 2008).

1.7.4 Chemiluminescence

Chemiluminescence reactions can be used to measure NO_2 concentrations by monitoring the generation of electromagnetic radiation, typically visible light, which is released during a reaction. Measuring NO_2 concentrations can be achieved by various methods of chemiluminescence, such as the conversion of NO_2 to NO using thermal converters or photolytic converters. The NO_2 concentration is estimated by subtracting the instrument response when bypassing the converter from the response when passing the air sample though the converter (U.S. EPA, 2000b). Luminol reacts with NO_2 in water emitting visible radiation of about 465 nm, where direct, real time measurements can be achieved with a photomultiplier tube (U.S. EPA, 2000b). Portable detectors are available to use in the field such as the Scintrex LMA-3 giving continuous monitoring (Ross, 1996).

1.7.5 Electrochemical sensors

As described for CO, electrochemical sensors are available for measurements of NO_2, where the current produced from the reduction of NO_2 can be used to calculate the concentration of NO_2. Known interfering gases include CO, NO, SO_2, hydrogen sulphide and chlorine.

1.7.6 Manual active sampling

Manual sampling can be carried out onsite and analysed in the laboratory, methods include sodium arsenite, suitable for up to 24 hours sampling and Saltzman which is for short term sampling of up to 2 hours. For the sodium arsenite method, NO_2 is collected from an air sample by being passed through a solution of sodium hydroxide and sodium arsenite forming sodium nitrate where the concentration can be determined colorimetrically by reacting the nitrate with phosphoric acid, sulphanilamide and a dye solution and measuring the resultant coloured azo dye using a spectrophotometer (Goyal, 2003; Goyal and Gavane, 2005). The Saltzman method is similar, using sulphanilic acid and glacial acetic acid as the absorbing media for NO_2, where once absorbed a pink coloured product can be measured at 550 nm (Goyal and Gavane, 2005). Absorption efficiency is around 82% and 74% for sodium arsenite and Saltzman respectively with a measurement range of 20 - 750 µg m^{-3} and 0 - 9400 µg m^{-3} (Goyal and Gavane, 2005).

1.8 Volatile organic compounds

1.8.1 Sources and occurrence in indoor air

Vast arrays of organic compounds are present in indoor air, with indoor air levels of VOCs usually higher than outdoors. Indoor sources include metabolic products from organisms, emissions from building and furnishing materials, consumer products (such as paints, pesticides, cleaning products and cosmetics), electrical products (such as computers), environmental tobacco smoke and combustion appliances.

There are several definitions for VOCs; including all organic compounds resulting from human activity, excluding methane, that are capable of reacting with NO_X photochemically to produce oxidants, such as ozone (Zevenhoven and Kilpinen, 2001). Ozone is a powerful oxidiser with a WHO guideline limit in air of 100 µg m^{-3} for an 8 hour mean as ozone is an irritant that can affect the respiratory system and is linked with daily mortality (WHO, 2006).

VOCs can be classified by boiling range as described in Table 1-2 (WHO, 1989), but it is more common to refer to any airborne organic compound in the indoor environment under normal conditions as a VOC. Semi-volatile organic compounds (SVOC) tend to occur in lower concentrations than VOCs due to their relatively low vapour pressure and sources include plasticisers used in polymeric materials, pesticides and combustion producing PAHs, (Crump *et al*., 2002). Microbial volatile organic compounds (MVOC) are released from metabolism of fungi (Crump *et al*., 2009), and are associated with moisture problems.

Table 1-2: Classification of indoor organic pollutants

(Source: WHO, 1989)

Description	Abbreviation	Boiling point range (℃)
Very volatile organic compounds	VVOC	<0 to 50 -100
Volatile organic compounds	VOC	50 - 100 to 240 - 280
Semi-volatile organic compounds	SVOC	240 -280 to 380 - 400
Particulate organic matter	POM	>380

The category of very volatile organic compounds (VVOC) includes the compound formaldehyde, which is widely studied due to its release from a range of indoor sources namely wall insulation and chip board (Communities and Local Government, 2004). Formaldehyde is an irritant and is classed as a human carcinogen by the WHO International Agency for Research on Cancer

(2006), and its toxicity was recently the subject of a major review by the US Environmental Protection Agency (U.S. EPA, 2011), which defined formaldehyde as a carcinogen after inhalation or oral exposure. Offermann (2010) found that there was a significant inversely correlated relationship between formaldehyde and the air exchange rate in 108 newly built Californian homes.

Although wood products and insulation are the primary sources of formaldehyde in the home, combustion from open fires may also be important. Secondary formation of formaldehyde can occur through the oxidation of other VOCs, formaldehyde concentrations were found to be higher in homes with lower air exchange rates compared to homes with higher air exchange rates. Also concentrations can reach 0.2 mg m^{-3} in the close vicinity of tobacco smoking indoors (WHO, Regional Office for Europe, 2010). Formaldehyde is a colourless gas that is highly reactive and soluble in water and other polar solvents, a WHO guideline limit of 0.1 mg m^{-3} for 30 minutes has been recommended in order to prevent short term effects on lung function and also long term carcinogenic effects (WHO, Regional Office for Europe, 2010).

Along with CO and NO_X, formaldehyde is a key pollutant from biomass combustion and cooking activities in the home (Salthammer *et al*., 2010). Residential wood combustion in America was found to be a source of benzene, toluene and xylenes (Mcdonald *et al*., 2000). Swedish experimental data of emissions from a woodstove using different wood types observed formaldehyde, acetone and acetaldehyde to be the most abundant of the 16 volatile ketones and aldehydes observed (Hedberg *et al*., 2002).

VOCs are usually emitted in greater amount from new materials and products; emission rates are influenced by source, temperature, relative humidity, ventilation, age of materials, occupants and their behaviour and activities. Total volatile organic compound (TVOC) concentrations in new office buildings can often be up to 100 times greater than outdoor air levels (Bernstein *et al*., 2008). Health effects at low levels are generally irritation and odours, but at elevated

concentrations acute toxic neurological effects can be observed (Communities and Local Government, 2004).

Indoor monitoring of 26 VOCs continuously over seven days during winter in 96 homes in Quebec, Canada indicated that combustion sources and recent renovation activities contributed to a rise in concentration of some VOCs, newer homes generally had higher concentrations of VOCs (Héroux *et al*., 2008). Air exchange rates ranged from 0.1 – 0.6 ach and chloroform was found to be negatively correlated to air change rate. Hexane levels were higher in homes with attached garages. For homes with gas and oil as the fuel for heating, benzene, toluene, styrene, ethylbenzene and 1,2,4-trimethylbenzene concentrations were higher. Benzene and styrene concentrations were also associated with the number of cigarettes smoked in the home.

Acetaldehyde was found to be elevated during a gas oven self-clean cycle at a concentration of 434 µg m^{-3} and also formaldehyde at 417 µg m^{-3}, both of which were observed during a 5 hour test (Fortmann *et al*., 2001). The authors comment that the aldehyde measurements were limited but could be an indication that cooking, particularly gas cooking and electric ovens operating self-cleaning, may have a significant impact on exposure.

Personal exposure of American women to VOCs was monitored using pumped Tenax TA tubes (Heavner *et al*., 1995). Subsequent analysis was performed using GC on the collected samples, only households with a smoking husband and homes with gas heating were identified as contributing factors to indoor air benzene levels.

Measurement of TVOC as an indication for IAQ is a debatable method as the value will represent a mixture of different compositions, with individual compounds contributing variously to the TVOC value and posing different risks to health. The TVOC value can be compared against a guideline value of 300 µg m^{-3} averaged over 8 hours, as adopted by the Building Regulations (Communities and Local Government, 2004).

In a report on IAQ and ventilation in homes built in compliance with 2006 Building Regulations, the sample of homes monitored had acceptable levels of formaldehyde, but in over half the sample of the homes observed TVOC levels exceeded the long term exposure guideline of 300 µg m^{-3}, two of which were in excess of 600 µg m^{-3} (McKay *et al*., 2010).

1.8.2 Methods of measuring volatile organic compounds

Many standards are available for sampling strategies and measurements for the vast array of VOCs, further details are given in Appendix B.

1.8.3 Sorbent tubes

As described in the BS ISO 16000 indoor air measurement series of standards (Appendix B), these methods can be active or passive sampling methods with subsequent analysis performed in the laboratory. The method of monitoring VOCs in ISO 16000-6:2006 is based on reversible sorption and uses Tenax TA sorbent tubes, actively sampled and analysed by thermal desorption (TD) and gas chromatography (GC) with detection by mass spectrometer (MS) or flame ionisation. For monitoring carbonyl compounds specifically air is drawn through a reactive medium coated with 2,4- dinitrophenylhydrazine (DNPH) which converts them to their corresponding hydrazones which can be efficiently recovered and measured with high sensitivity, precision and accuracy using HPLC (high performance liquid chromatography).

1.8.4 Photo ionisation detectors

Photo ionisation detectors (PID) are non-specific and give TVOC measurements for the air under examination; differentiation of individual compounds and their concentrations cannot be obtained (Ion Science, 2008). PIDs work by passing the sample gas over the PID lamp, which emits UV light inducing photoionisation breaking of molecules into positively and negatively charged ions. These ions generate a current proportional to the number of particles collected by two electrodes, so a concentration of the sample gas can be obtained. Equivalent readings for particular gases can be estimated using

software on the instrument. Such monitors can be used to carry out continuous onsite measurements and log data.

1.9 Particles

Particles in the air arise from various sources, natural (such as forest fires and pollen) and as a result of human activity (such as combustion products and industrial processes). Particles can be classified as primary where release is directly into the atmosphere, or secondary where particles are formed by chemical reaction in the atmosphere (Crump *et al*., 2002). PM is the most heterogeneous air pollutant category consisting of a range of suspended material (Jantunen *et al*., 2008). Airborne particles can affect human health in a number of ways including discomfort, irritation, respiratory and cardiovascular problems as well as being linked with increased mortality.

With regard to indoor air, particles of concern tend to be PM_{10} and particles smaller than this, as larger particles settle out of the air through sedimentation. PM_{10} is airborne PM with an aerodynamic diameter of 10 µm or less and $PM_{2.5}$ is less than 2.5 µm. Sizes of particles that can be inhaled are approximately 100 µm or less and respirable sizes which can penetrate the lungs are thought to be of 5 µm or less. It was found that in terms of number, more than 80% of particles in an ambient urban environment were smaller than 0.1 µm, which fall into the ultrafine region (Morawska *et al*., 1998). The large surface area on airborne particles allows toxins, such as polycyclic aromatic hydrocarbons (PAH) to accumulate on their surfaces.

Indoor PM can arise from a number of sources such as tobacco smoke, cooking, heating, occupant products and activities, building materials, dust and infiltration of outdoor sources (Bernstein *et al*., 2008). Combustion of biomass fuels can be an important source of particles, largely of $PM_{2.5}$ in size (WHO, 2006). PM can react with other indoor air pollutants which can have adverse health effects and PM can also harbour toxic pollutants into the airways which can have a proinflammatory effect (Bernstein *et al*., 2008). $PM_{2.5}$ can remain suspended in air for extended periods of time and can be transported over long

distances by movement of air. Health effects are mainly related to the respiratory and cardiovascular system and all populations are affected, with increased susceptibility to vulnerable groups such as the young and the elderly. Coarse indoor generated PM_{10} and $PM_{2.5}$ tend to deposit in the nasal, pharyngeal and laryngeal regions of the respiratory systems whereas finer particles can penetrate deeper.

PM and other such air pollutants have been linked to cardiovascular and lung disease cases, but it is also thought that they may have contribution to intestinal disease although a causative link can currently be linked (Beamisha *et al*., 2011). Exposure of air pollutants to the bowel can occur through ingestion of food and drink and also through mucociliary clearance of PM from the lungs.

Guidelines for acceptable PM levels in ambient air have been established for $PM_{2.5}$ and PM_{10} levels. Although PM_{10} is more widely studied as it covers coarse and fine particles ($PM_{2.5}$). The WHO used studies based on $PM_{2.5}$ as an indicator, converting these values to apply to PM_{10} by applying a $PM_{2.5}$ / PM_{10} ratio of 0.5 (WHO, 2006). Short term and long term health effects are observed so guidelines are required for both indicators of PM pollution for both time periods;

$PM_{2.5}$: 10 µg m^{-3} - annual

25 µg m^{-3} - 24 hour

PM_{10}: 20 µg m^{-3} - annual

50 µg m^{-3} - 24 hour.

The annual average for $PM_{2.5}$ represents the lower end of a range where significant associations with mortality and long term exposure of $PM_{2.5}$ are observed. The short term guidelines are aimed to protect the population against peaks of pollution which otherwise lead to illness and death (WHO, 2006).

A study of air pollution in retirement homes in Los Angeles found indoor measurements of $PM_{2.5}$ in one home to have an average concentration in the

summer months of 37.51 µg m^{-3}, which was higher than the average outdoor concentration for this home during this period which was 24.86 µg m^{-3}. The indoor average during the winter months of October to December was 12.66 µg m^{-3}. The high indoor concentrations observed during the summer months were linked to indoor sources with use of a gas stove/oven which was less during the winter months (Polidori *et al*., 2007). Designing buildings and the ventilation to minimise the infiltration of particles from outdoors is an efficient way to reduce indoor exposure and health risks corresponding to PM (Hänninen *et al*., 2005), but indoor sources may still be a problem to health.

Residential wood combustion can be a source of particles among other pollutants such as CO (Lévesque *et al*., 2001), and wood combustion has been shown to account for an increase in a local source of $PM_{2.5}$ and PAH in a 2007 Danish study monitoring particles generated from residential wood burning appliances (Glasius *et al*., 2008).

PM_{10} concentrations were found to be significantly higher during cooking in homes without chimneys compared to those with chimneys in Lao and also in homes that used wood for combustion fuel for cooking (Morawska *et al*., 2011). Despite this, CO concentrations were not significantly higher suggesting incomplete combustion was not the major contributor accounting for the increased PM levels.

Toxicity of ambient PM collected in a village with wood burning stoves and from a rural background area in Denmark were compared to wood smoke PM from wood stoves and assessed in cultured human cells (Danielsen *et al*., 2011). The wood smoke PM induced the formation of reactive radical species, DNA damage, contained more PAH and was smaller than the PM from ambient air. It was also observed that combustion under conditions of high oxygen produced smaller particles, predominantly in the ultrafine to fine region and had higher PAH concentrations than in low oxygen combustion. The results suggest wood smoke PM in the same quantity is more toxic than ambient air PM.

In a multi-seasonal study, 108 new, single-family detached Californian homes were monitored for various air pollutants; $PM_{2.5}$ along with formaldehyde, were the only contaminants to exceed exposure guidelines (Offermann, 2010). Leaderer *et al*. (1999) monitored $PM_{2.5}$ and PM_{10} in American homes over a 24 hour period in both summer and winter and found that kerosene heater use during the winter monitoring period resulted in a significant increase in $PM_{2.5}$ and their use on average added approximately 40 µg m^{-3} to the background residential levels of 18 µg m^{-3}.

An audit on IAQ in a Portuguese hotel found that in some of the monitored rooms, insufficient ventilation rates and high particle concentrations were observed (Asadi *et al*., 2011). Measurement of suspended PM_{10} in two out of the 3 monitored rooms exceeded the Portugal national IAQ guideline of 150 µg m^{-3}, CO concentrations were low and did not exceed 0.6 ppm.

1.9.1 Methods of measuring particulate matter

Particle measurements are usually of mass concentration and can normally be achieved by drawing air with a sampling pump through a size-selective sampling inlet to select the size to be monitored and delivering this air to a filter or detection system. The cheapest methods are gravimetric, weighing filters before and after use with a sensitive balance of typically 1 µg resolution, using sampling times of typically two days to get a weighable amount. Other methods include real time measurement methods such as light scattering techniques and Tapered Element Oscillating Microbalance (TEOM), both of which can be large, noisy and expensive. The TEOM deposits particles on a small filter causing changes in the frequency of oscillation that is directly proportional to the deposited mass (Crump *et al*., 2002).

1.9.2 Ultrafine particles

UFP are defined as those with a diameter of less than 0.1 µm and arise as the by-product of chemical reactions at high temperatures, such as combustion, cooking fumes, cigarette smoke and even toner from copiers and printers

(Morawska, 2010). Formation is not fully understood but UFP can originate from evaporation of SVOCs forming particles through either homogenous nucleation or secondary particle formation involving ozone. Their chemical properties vary depending upon source and post-formation process (Morawska *et al*., 2004). Limited information is known about safe limits for human exposure to UFP and although previously UFP have been linked with human health issues, insufficient evidence is available to evaluate a recommended guideline for exposure concentrations (WHO, 2006).

Due to their size, measurements for UFP are made as number concentration rather than mass concentration as they have a low mass which is insignificant in comparison to their larger particle counterparts (Morawska *et al*., 2004). On a number basis, UFP are major components of airborne PM (Zhang *et al*., 2010). To determine particle properties such as mass concentration, size and chemical composition air samples must be collected prior to a laboratory investigation, which requires expensive equipment.

Particle concentrations vary depending on the type of environment, such as a few hundred particles per cubic centimetre (pt cm^{-3}) in areas not influenced by human activity to 100,000's pt cm^{-3} in roads and tunnels. In comparison to PM_{10} and $PM_{2.5}$ where only elevated levels are seen by about a quarter, exposure to UFP at urban roadsides are highly elevated above ambient levels (Morawska *et al*., 2004). The concentration at which it is thought to impact humans is around 50,000 particles cm^{-3}, the sort of levels which may be observed with environmental tobacco smoke, smog and with work place activities such as welding (Philips Aerasense solutions, 2010).

The concentration of UFP is found to correlate linearly with the concentration of CO from traffic sources in ambient air (Wilhelm and Ritz, 2005). Indoor levels of UFP do not necessarily correlate with outdoor levels, as observed in a recent study monitoring levels in classrooms, which found that during certain activities such as cleaning and painting, indoor UFP levels could be twice as high compared to those outdoors (Morawska *et al*., 2009). The infiltration factor of

outdoor UFP increases with particle size and air exchange rate (Rim *et al*., 2010).

Previous studies have shown how the large surface area to volume ratio of UFP have a more toxic effect than larger particles, because chemical reactions can occur on these surfaces and they act as vehicles for transporting other contaminants (Zhang *et al*., 2010; Lubick, 2009). Inflammation in rats has been observed on exposure to UFP (Brown *et al*., 2001) and inflammation was also greater with UFP than larger fine particles (Renwick *et al*., 2004).

It has been suggested that adverse effects on cardiac function and haemostasis may occur as UFP diffuse from the lungs into the blood stream and are distributed to the organs (Nemmar *et al*., 2001; Nemmar *et al*., 2002; Takenaka *et al*., 2001). More recently, it has been claimed that exposure to UFP may cause heart disease, due to inflammation induced by free radical oxidation of chemicals located on the surface of UFP promoting hardening of the arteries, in mice, by deactivating high density lipoprotein cholesterol which would usually act to counter inflammation (University of California, Los Angeles, 2008).

UFP and CO concentrations in a transport microenvironment were more influenced by the volume of traffic than $PM_{2.5}$, and UFP and CO were also significantly impacted by temperature and wind speed (Kaur and Nieuwenhuijsen, 2009).

Although there are no guideline values available for UFP and there is limited knowledge regarding them, they are typically generated by combustion processes. Cooking studies have shown how high emissions of PM including UFP can be produced and concentrations and sizes vary depending upon the style and method of cooking (Zhang *et al*., 2010; Wallace *et al*., 2004), with frying shown to emit the largest amount. Other factors contributing to the high concentrations include higher cooking temperature, and the extract ventilation being turned off (He *et al*., 2004). In a study looking into UFP generated by gas and electric cooking, it was found that high concentrations were generated by gas combustion, frying and cooking fatty foods whilst electric rings and grills

may also generate particles from their surfaces (Dennekamp *et al*., 2001). Frying bacon on a gas cooker produced the highest peak of UFP in the various hob, oven and grill experiments, of 590,000 UFP cm^{-3}, which was significantly higher than 159,000 UFP cm^{-3} when bacon was fried on an electric hob. UFP loss rate was also measured, and the 50% loss rate was found to be 30 minutes, which was twice as fast as the NO_x loss rate, and thought to be due to coagulation of particles. The authors conclude that toxic concentrations of particles may be observed in poorly ventilated kitchens.

Wallace *et al*., (2008), studied size distributions and emissions of UFP generated from a gas stove, an electric stove and an electric toaster. The highest observed peak concentration occurred when a gas burner was on with no pans (200,000 UFP cm^{-3}). Typical background concentrations were found to be around 1,000 UFP cm^{-3}, which in as little of 4 minutes of cooking can increase concentrations by 100 times. Air change rates were also measured and on average were 0.23 h^{-1} and ranged from 0.097 – 0.57 h^{-1}.

Gas flames produce UFP and levels increase with the addition of pans to and with more cooking activity occurring within the pans. Over 5 – 15 minute cooking periods, most particles generated were in the ultrafine range and particle emission rate over 44 cooking episodes using gas as the fuel source was 10^{14} pt h^{-1} (Wallace *et al*., 2004).

Personal exposure to UFP was monitored and documented using personal condensation particle counters kept close to the participant over a 3 year period (Wallace and Ott, 2011). Combustion and heating elements were found to increase the number of UFP. The highest peak concentration (432,000 pt cm^{-3}) was observed from gas cooking, other highly elevated levels of UFP were observed with the use of a hairdryer and curling iron, using house cleansers, using an electric toaster oven and cooking with a gas stove. Cooking using the gas oven was also associated with the highest 1 hour average (386,000 pt cm^{-3}). Apart from gas cooking, use of a curling iron also produced a high 1 hour average concentration. It was also observed that the UFP count in restaurants were relatively high (around 95,000 pt cm^{-3}) and higher than in vehicles (around

30,000 pt cm^{-3}). Exposures from indoor sources were higher than for measurements taken outdoors.

A Canadian study looking into the contribution of home heating systems to UFP exposure found that homes with electric heaters and wood stoves had greater overnight baseline concentrations than homes using oil and gas furnaces (Weichenthal *et al*., 2007).

Peak numbers of UFP observed in the breathing zone when frying beefsteak were higher when cooked on a gas stove with margarine (896,000 pt cm^{-3}) and soya bean oil (893,000 pt cm^{-3}) compared to when the same frying fats were used in the same procedure on an electric stove, 60,000 pt cm^{-3} and 146,000 pt cm^{-3} respectively (Sjaastad *et al*., 2010). The gas stove also produced higher levels of PAHs, aldehydes and particles. It was also observed that the size of the UFP in the gas cooking were smaller than when electric was used to cook. The highest level of mutagenic aldehydes and total particles were observed when cooking with gas. Sjaastad and Svendsen (2008) also looked at emissions of particles and aldehydes in the breathing zone of the cook emitted when frying beefsteak using margarine, rapeseed oil, olive oil and soya bean oil on electric cookers only. Margarine gave a significantly higher particle mean of 11.6 mg m^{-3}, whereas the other cooking fats had means less than 1.5 mg m^{-3}. Margarine also gave rise to the highest concentration of aldehydes, this study suggests that preferences of the occupants cooking can significantly impact pollutant levels within the home.

Sjaastad and Svendsen (2009) monitored exposure to PAHs, aldehydes and particulate matter in the breathing zone of the cook in three Norwegian restaurants. One of the three had the use of gas cooking; it was found this restaurant had the lowest total particle mass concentration, but higher levels of mutagenic aldehydes.

Indoor sources of UFP were investigated in a single home in the USA over a 37 month sampling period, where 5 minute averages were taken during various activities (Wallace, 2006). The average UFP concentration with no source was

2,500 pt cm^{-3} and greater than 20,000 pt cm^{-3} when sources were active with an average duration of elevated particle concentration ranging from 20 minutes to 3 hours. Gas appliances, use of an electric toaster and burning of candles and incense were observed to provide peaks in UFP concentrations from indoor sources, with the highest average concentration ranging from 35,000 – 50,000 pt cm^{-3} from gas cooking.

1.9.3 Methods of measuring ultrafine particle

As previously mentioned, UFP are usually measured on a number basis per unit volume rather than mass per unit volume. This is the principle for the technology that is used in condensation particle counters such as the P-TRAK UFP counter which outputs and logs real-time concentration measurements in units of pt cm^{-3} (TSI Incorporated, 2009). This technology works by taking in air via suction pump; the incoming particles pass through a saturator tube where they mix with an alcohol vapour and pass through a condenser tube forming a larger droplet by condensation of the alcohol onto the particle. These formed droplets are then passed through a laser beam and detected by the scattering of the light by a photo-detector. The Electrical Low Pressure Impactor and Scanning Mobility Particle Sizer are two types of instruments that can monitor different size ranges of UFP but tend to be expensive (Crump *et al*., 2002).

1.9.4 Polycyclic aromatic hydrocarbons

PAHs are organic compounds composed of two or more aromatic rings, the rings also include heterocyclics where carbon atoms are substituted with elements such as nitrogen or sulphur. Typical flue gas PAHs are of 2 – 7 aromatic rings in size, such as benzo[a]pyrene (BaP) a five ringed hydrocarbon. The simplest PAH, naphthalene, falls in the VOC category and has a boiling point of 218 ℃, PAHs with four or more aromatic rings tend to be non-volatile and are located as deposits or absorbed by particles.

In ambient air, the majority of PAHs are adsorbed onto particles and only a minor fraction exists as volatiles (WHO, Regional Office for Europe, 1987).

Combustion at about 500 – 800 ℃ of carbon based fuels may lead to PAH formation resulting from incomplete combustion this this is dependant on the type of fuel used (Zevenhoven and Kilpinen, 2001). In industrialised countries tobacco smoke has the greatest impact on indoor PAH concentrations, cooking and heating with unvented or flueless solid fuel stoves can also be a main contribution (WHO, Regional Office for Europe, 2010). The cooking method also plays a part and higher fat content foods tend to increase production of PAHs.

Indoor sources of naphthalene include unvented kerosene heaters, wood smoke and tobacco smoke, but it is best known as a moth repellent. It is suspected to be a human carcinogen and has an indoor annual concentration guideline set by the WHO of 0.01 mg m^{-3} (WHO, Regional Office for Europe, 2010).

BaP is the most widely studied PAH and BaP concentrations are used as an indicator for PAHs. Indoor sources of BaP include cooking processes and combustion appliances. BaP in urban areas of Europe range from 1 - 10 ng m^{-3} while in rural areas are less than 1 ng m^{-3} (WHO, Regional Office for Europe, 2000). BaP is considered a human carcinogen and chronic inhalation may cause respiratory problems and irritation, while chronic skin exposure may have detrimental dermatological effects, animal studies of BaP. The routes of human exposure for BaP are via inhalation, ingestion and skin exposure and once absorbed it is rapidly distributed to organs such as the liver and kidney (Bull, 2008). The WHO considers all indoor exposures to PAHs as relevant to health due to evidence that PAHs are genotoxic carcinogens with no safe threshold (WHO, Regional Office for Europe, 2010).

Six French homes which regularly burn wood in stoves and fireplaces were found to have elevated PAHs and NO_2 concentrations due to the burning of wood (Mandin *et al*., 2009). $PM_{2.5\ \&\ 10}$ were also impacted by wood burning in some homes as was benzene, but indoor concentrations of formaldehyde were not found to be influenced.

1.10 Sulphur dioxide

SO_2 is a combustion gas produced from fossil fuels, such as coal, containing sulphur. When inhaled it acts as an irritant, stimulating nerves in the lining of the nose, throat and lungs, due to its acidity, which may lead to breathing problems to those exposed, such as coughing and narrowing of the airways (Department of the Environment, 1996). Other adverse health effects include increased short term respiratory morbidity and mortality (Bernstein *et al*., 2008). Asthma and chronic lung disease sufferers are among those that are more susceptible to affects upon exposure, as their airways are often already narrowed, inflamed and easily irritated. SO_2 is one of the major components of smog seen in major smog episodes in 1952 London, which saw increased numbers of chest illnesses and excess deaths in susceptible groups, mainly the elderly with heart and lung disease.

Acute effects have been observed in controlled chamber studies on volunteers, where rapid responses have been observed within a few minutes of inhalation and effects were enhanced by exercise, with a greater effect on exercising asthmatics (WHO, Regional Office for Europe, 2000). The UK Clean Air Act of 1956 saw a reduction in use of sulphur based fuels and an increase in use of natural gas and electricity fuels. This was required to reduce smog and SO_2 levels because SO_2 is a precursor of acid rain and PM (Department of the Environment, 1996). As a result of the decrease in the use of coal and open coal fires in the UK, SO_2 is greatly reduced as a source of pollution and studies suggest that levels observed in UK homes with kerosene heaters are unlikely to be a problem (Communities and Local Government, 2004).

There was little basis for separating contributions of individual pollutants to health effects when WHO guidelines for SO_2 were introduced in 1987, as values for SO_2 in air were linked to values for PM. More recently a study in Hong Kong relating to a major reduction in sulphur content of fuels over a short time period observed substantial reductions in associated health effects, leading to revision of the WHO guideline, although there is still uncertainty about whether SO_2 is

the pollutant responsible for the observed health effects or if it is due to associated particles (WHO, 2006). The WHO guideline values are:

20 µg m^{-3} - 24 hour

500 µg m^{-3} - 10 minute.

1.11 Summary of guidelines for indoor air pollutants

A summary of the guideline values for the air pollutants of interest, namely CO, NO_2, VOCs, SO_2, particles and PAHs are summarised in Table 1-3 with the average time periods over which these values of exposure are not to be exceeded.

Table 1-3: Recommended guideline values for selected air pollutants

Air pollutant	Recommended value & average time period	Notes
CO[A]	87 ppm – 15 minutes 52 ppm – 30 minutes[B] 26 ppm – 1 hour 9 ppm – 8 hours. 6 ppm – 24 hours	The 30 minute guideline has been dropped in the 2010 WHO Indoor Air Quality Guidelines and the 24 hour guideline has been added.
NO_2[A]	40 µg m^{-3} – annual mean 200 µg m^{-3} – 1 hour	There is no guideline value for NO as current evidence is insufficient.
VOCs[B]	Toluene: 0.26 mg m^{-3} – 1 week Styrene: 0.26 mg m^{-3} – 1 week Formaldehyde[A]: 0.1mg m^{-3} – 30	There is no recommended WHO TVOC value. Benzene has no safe

	minutes Benzene[D]: 5.0 µg m^{-3} – Annual TVOC[E]: 300 µg m^{-3} – 8 hours	level of exposure to be recommended by the WHO[A], as it is a known carcinogen.
SO_2[B]	20 µg m^{-3} – 24 hour 500 µg m^{-3} – 10 minute	
Particles[C] $PM_{2.5}$: PM_{10}:	10 µg m^{-3} – annual 25 µg m^{-3} – 24 hour 20 µg m^{-3} – annual 50 µg m^{-3} – 24 hour	UFP currently have insufficient evidence to evaluate a recommended guideline value
PAH	BaP[F] - 1 ng m^{-3} – not be exceeded in ambient air Naphtalene[A] – 0.01 mg m^{-3} – annual	BaP chosen as indicator for PAHs. BaP has no safe level of exposure to be recommended by the WHO[A], as it is a known carcinogen.

A. WHO, Regional Office for Europe, 2010
B. WHO, Regional Office for Europe, 2000
C. WHO, 2006
D. Department of Health, Committee on the Medical Effects of Air Pollutants, 2004
E. Communities and Local Government, 2004
F. The European Parliament and the Council of the European Union, 2005

The European Parliament and the Council of the European Union provide directives which are regulatory standards not to be exceeded in ambient air, whereas the WHO provide recommended guidelines for ambient and indoor air which are not mandatory. Communities and Local Government values for TVOC are performance values within AD F for the indoor environment and can be used to demonstrate compliance with the AD F requirements. The Department

of Health recommend guidelines that are only applicable to the home environment.

Values in Table 1-3 are averages over a given time period. Guideline values are used to protect the general population and the levels identified should not pose significant health risks if slightly exceeded, as long as this is not a common occurrence, as a margin of safety is generally applied so significant effects will not appear when the levels are exceeded, but special groups may still be affected at low concentrations (Department of Health, Committee on the Medical Effects of Air Pollutants, 2004).

1.12 Modelling of indoor pollutant concentrations

The benefits of IAQ modelling include the ability to use data from past studies to input into various scenarios and situations and thereby assess the effect of changing model parameters, such as altering ventilation rates and emission rates. This could be used to observe worst case scenarios and to compare modelled data to health guidelines for air pollutants. It also allows for data to be obtained by simulation of the environment of interest that could be unethical and dangerous to human health if observed in a natural setting. Disadvantages include that as it is only a simulation, certain factors may not be accounted for such as limiting the number of sources of air pollution, and so the results may be unrepresentative of real situations as underestimates or overestimates of emissions may occur. Modelling the distribution of pollutants throughout the home with various ventilation patterns and configurations is difficult when using microenvironment models and the model may use unrealistic fixed activity patterns (Dimitroulopoulou *et al*., 2006). Real situations will be more complex than modelled scenarios as the possibility of complex mixtures of substances which could combine to detrimentally affect health, whereas at lower concentrations and alone they may not be observed to affect health at all.

The 2000 Building Regulations AD F states that the ventilation rates should be between 0.5 to 0.75 air changes per hour (ach) to ensure the relative humidity throughout the home is below 70% and thereby prevent mould growth, but this

may not be adequate to control other pollutants such as NO_2 and VOCs (Communities and Local Government, 2004). The Building Regulations AD F requires extract ventilation to the outside for each kitchen, utility room, and bathroom and for sanitary accommodation (Communities and Local Government, 2010b). An assumption of zero air permeability, therefore no infiltration, is made for new dwellings in AD F solely relying on ventilation systems, but alternate ventilation options have assumed infiltration rates of 0.05 ach and 0.15 ach, with lower purpose provided ventilation requirements for the latter.

Various tools are available for modelling of air in various settings, like the Exposure Modelling Tool (National Institute for Health and Welfare, 2009), which allows concentration, exposure, intake and intake fraction to be calculated for a defined box room, where the air exchange rate is also user defined, with various links to external and internal sources of information such as rates of release and intake values and also links to other models.

The EPA's Exposure Factors Handbook (EPA, 1997) compiles selected data from various sources that summarises data on human activity which may affect exposure to environmental contaminants, such as indoor air pollutants and recommends typical values to use in exposure models. The EPA have many models such as the Multi-Chamber Concentration and Exposure Model for estimating average and peak indoor concentrations and the inhalation exposure released from products or materials in residential settings and a human inhalation model, the Air Pollutants Exposure Model. The models can incorporate the option of sinks, where the airborne chemical can reversibly or irreversibly absorb onto a surface.

A paper evaluating the US EPA's probabilistic CO exposure model, pNEM/CO, implies that the model underestimates personal exposure of people exposed to high concentrations of CO (Law *et al*., 1997). Model parameters and empirical constants were used, which in real monitoring situations would vary, such as using a constant secondary-smoke CO value of 1.6 ppm and constant air

exchange rates. The modelling also used only two indoor sources; passive smoking and gas stoves.

An investigation of pollutant concentration exploring different scenarios used results obtained from controlled chamber experiments to further investigate emission release using an indoor air model to represent a house where various parameters could be altered such as pollutant emission rate, wind direction and house airtightness (Upton *et al*., 2004). To supply information to input into the model, representative emission rates were taken from the experimental data obtained to evaluate pollutant levels in the home for comparison with guideline values. The model used, BREEZE, allowed parameters such as the geometry and air paths to be illustrated by the user. Typical CO emission rate was found to be 0.0058 g min^{-1}, for a flueless cabinet heater on low heat position and maximum emission rate of 0.085 g min^{-1} for CO from a flueless cooker with two hobs with pans on maximum heat. Assumptions and variables in the simulations included airtightness, background ventilation, internal doors opened and outdoor temperature typical for that of winter and spring/autumn.

The modelled conditions using a single source of a flueless gas combustion located in the living room found that with the maximum emission rate and the living room door closed, the WHO guidelines and the Health and Safety Executive (HSE, 2007) occupational exposure limits of 200 ppm for 15 min and 30 ppm for 8 hours would be exceeded. For typical emission rates, only the WHO 8 hour mean would be exceeded when the living room door is closed. One of the study findings was that WHO guideline concentrations for CO are likely to be exceeded in situations where there is extended use of flueless gas appliances and also in instances over short periods of time where emission rates of the appliance are greater than that typically found. With the source located in the living room; opening internal doors reduced levels by 75 – 80% in the living room, CO in the living room was found to be 10% higher than in the master bedroom and NO_2 modelling found that there was a large difference from the room containing the source to that of the bedroom due to reactions with interior materials.

Dimitroulopoulou *et al.,* (2006) describe a model (INDAIR) used to predict CO and other air pollutant concentrations in microenvironments within UK homes with emission scenarios of cooking, smoking and no source. The modelled predictions were found to be generally consistent with other data on indoor concentrations in UK homes. Mean concentrations from the model varied most with changes in outdoor concentrations, airtightness and deposition velocities in scenarios where there was no source. Peak concentrations in source rooms varied most with changes in emission rates and room sizes. Annual average CO concentrations were dominated by infiltration of outdoor air. The authors comment that it is important to incorporate infiltration of outdoor pollutants which are also generated indoors. The three microenvironments modelled for the home were the kitchen, living room and bedroom due to these rooms being the most important for occupant exposure either due to the time spent in them and/or the emission sources located within these rooms. Mean room volumes were taken from a sample of estate agent's data and used for the modelling parameters. Assuming the rooms were furnished, area to volume for the home environment was calculated.

The simulation period was 24 hours at time intervals of 15 minutes. The majority of outdoor concentrations were based on data taken from a roadside location in Marylebone Road (London); the geometric mean of CO in the winter was 1.9 ppm for weekdays and 1.7 ppm for weekends and for the summer the geometric mean of CO was 1.7 ppm for weekdays and 1.4 ppm for weekends. CO can be considered as unreactive over the timescales considered for the modelling, therefore the levels would be controlled by ventilation. The highest concentration observed for the modelled CO data was the 8 hour running mean of 7.6 ppm observed in the gas cooking scenario in the winter weekdays.

1.12.1 Summary

Changes in UK building regulations introduced to help combat climate change are resulting in changes in the design and construction of homes, as well as methods of heating and ventilation and these could lead to new or increased

risks for the health of occupants. Energy efficient homes have airtight structures and therefore much lower rates of infiltration of external air and therefore appropriate use of ventilation provision by occupants is important to avoid problems associated with poor indoor air quality. Mechanical ventilation such as whole house ventilation and cooker hoods are not required by law to be operated and may be used inappropriately or turned off by occupants to save costs. Other ventilation provision such as opening windows and use of trickle ventilators is also dependent on occupant behaviour. Improper use could lead to very low rates of ventilation and accumulation of air pollutants, especially when indoor sources are present.

There are a wide range of sources of indoor pollutants but combustion processes are an important category, in particular because they emit carbon monoxide which is an odourless gas that causes significant numbers of deaths in homes in the UK. As well as CO, the combustion gases contain a wide range of other pollutants such as NO_2, VOCs and particulates which are a potential risk to health.

From the literature, typical CO concentrations in the home can be in the range of 0 – 50 ppm; generally houses have lower levels than 50 ppm but a greater range is of interest to account for peak concentrations and occupant behaviour. Peaks exceeding 50 ppm have been observed in studies reported in the literature during gas cooking and in homes where other activities increase indoor concentrations of CO, e.g. smoking, but generally peaks and averages are much lower. Although levels exceeding 1000 ppm have been observed, this was due to faulty appliances and unrepresentative samples were used in these studies.

There is a dearth of data about indoor air quality in newer energy efficient homes. Therefore to assess the possible risks from combustion sources in these homes there is a need for more measurement data and modelling studies to inform risk assessment.

2 Aims and objectives of the project

The primary aim of this project is to assess the risk to health of CO and other combustion products in energy efficient homes. Changes in UK building regulations introduced to help combat climate change are resulting in changes in the design and construction of homes, as well as methods of heating and ventilation and these could lead to new or increased risks for the health of occupants.

As part of measures to increase energy efficiency the requirements for the airtightness of building structures have steadily increased, leading to concerns that ventilation rates in homes may be reduced to below a level sufficient to maintain good IAQ. There is a particular concern with CO because it is a highly toxic and odourless gas responsible for approximately 25 accidental deaths per annum in the UK within the home, as well as possible sub-clinical adverse effects. Therefore the current project has sought to investigate concentrations of combustion gases in homes built since 2007 and assess the possible risks in these homes and future homes that will be built to even higher energy efficiency requirements. This has been undertaken by the development of an experimental and modelling approach. A number of specific objectives have been defined to achieve the overall aim of the project.

- Literature review – to assess the current literature on indoor pollution in homes and to define health based guidelines for combustion gases. This is to inform the assessment of the risks to occupants due to exposure to levels monitored in a field study as well as those given by modelling. The literature review also provides a basis for the selection of measurement methods and development of appropriate strategies and protocols for conducting the field and laboratory studies.

- Method development - Selection of appropriate instrumentation and methods for measurement of CO and other pollutants based on published literature and discussion with manufacturers. The associated costs are an important consideration as well as aspects such as

sensitivity and suitability for the home environment. This includes assessment of performance of monitoring equipment by laboratory and field tests prior to the main study.

- Study protocol - the project requires the development of a protocol for undertaking recruitment of homes to the study, conducting measurements of air pollutants and the recording of occupant activity in energy efficient homes as well as informing participants of findings of tests in their home. Existing literature will be used to develop an initial protocol and approval sought from the University (Cranfield Health) ethics committee.

- Pilot studies – the draft protocol requires refinement based on experience in the field and therefore will be applied in homes of colleagues and feedback received about ease of use of equipment and questionnaires and other suggested improvements. This will be taken into consideration to finalise the study protocol. The pilot also gives an important opportunity for the researcher's familiarisation with the monitoring procedure and equipment.

- Measurements of combustion generated pollutants – these are carried out in a sample of new (energy efficient) and refurbished homes according to the final study protocol. The emphasis is on determining CO by continuous monitoring in the kitchen and other habitable rooms with additional measurements of NO_2, particulates and some organic compounds in air. The initial target based on the available project resources was to undertake measurements in approximately 20 homes covering a range of building types. In addition measurements are undertaken according to the same protocol in a smaller sample of older (control) homes considered to be less energy efficient than the new homes.

- Modelling – this is used to assess the impact of a source such as a gas cooker emitting a defined rate of CO on concentrations in habitable

rooms. Varying emission rates and ventilation rates allow simulation of low ventilation rate (such as may occur in newer, energy efficient homes) scenarios and different source strengths and therefore extend the assessment of risks to health more broadly than is possible with the limited number of homes and scenarios that could be measured within the project.

- Data evaluation - using the information about sources and guidelines obtained by literature review, combined with the results of measurements and modelling, an assessment is undertaken of whether there are new or increased risks arising from the use of combusted fuels in energy efficient homes.

The study can only be considered as a preliminary investigation and not representative of the wide range of house types and different occupant behaviours that may influence levels of pollutants and amount of exposure of occupants in homes. A European economic crisis resulted in a much lower than the normal historic rate of building of new homes and therefore it was not practical to limit the field study to homes exceeding Building Regulations 2006 requirements during the study period. Nonetheless given the lack of available information about air quality in energy efficient homes the study aimed to provide valuable indicative data by studying homes built since 2007, including some innovative designs, and thereby provide a basis for recommendations for further work that could include evaluation of Code 4 to Code 6 rated homes.

3 Materials and methods

3.1 Selection of equipment

3.1.1 Carbon monoxide

The ICOM unit is able to measure background levels and is relatively low cost compared with NDIR methods whilst being unobtrusive to the occupants, enabling unattended operation and giving continuous real time monitoring measurements. The ICOM has also been used in previous studies and reported by its users as reliable for the purpose of monitoring homes for the presence of CO from combustion appliances. The monitor has a range of 0 – 500 ppm and a resolution of 0.1 ppm, with variable log intervals from 1 minute to 24 hours and a repeatability of 1% of signal.

The ICOM gas sensor has no cross sensitivity with SO_2, NO_2, NO, hydrogen chloride and hydrogen sulphide and the electrochemical sensor used (CityTech A3/EF) has an additional fourth auxiliary electrode to compensate for hydrogen cross sensitivity which is less than 5% (City Technology Ltd, 2004). Dräger tubes are cheap, easy to use and are small and because of this they could be used to gain measurements in space restricted areas, such as directly adjacent to cookers, where the measurements could be used to observe proximity effects. They also will give an average over an extended period of time as a longer exposure period than two days is normally used.

Lascar's EL-USB-CO300 electrochemical data logger is small (12.5 x 2.6 cm) and inexpensive with a range of 0 - 300 ppm, a resolution of 0.5 ppm, an accuracy of ±4% and is suitable for unattended logging of CO (Lascar Electronics, 2010). It does not have a digital display, the logging rates range from every 10 seconds to 5 minutes.

As part of the method development, work testing of the performance of the purchased CO logging equipment (the two ICOMs and the two Lascar ELs), was undertaken prior to the field measurements for the study and found that

there were no significant differences between the same types of monitors or between the different brands of monitors in the tests used (Appendix C).

3.1.2 Nitrogen dioxide

Passive NO_2 diffusion tubes were supplied and analysed by Gradko International Ltd. These acrylic tubes are fitted with an absorbent of 20% triethanolamine / deionised water as discussed in Section 1.7.3. Analysis is performed by UV / Visible spectrophotometer with reference to a standard nitrate solution calibration curve. The recommended exposure period is between 2 – 4 weeks, the detection limit for a 2 week exposure period is 1.6 µg m^{-3} with an uncertainty of ±10.9%. These diffusion tubes provide a better indication of lower levels that are likely to occur in the home and which are generally below the sensitivity of currently available electrochemical NO_2 loggers. The tubes also provide a relatively cheap method of detection.

3.1.3 Volatile organic compounds

FirstCheck+ 5000 PID (Ion Science Ltd), a multi-gas detector was available to monitor TVOC concentration, with a range of 1 ppb – 10,000 ppm. It has a digital display for real time monitoring information and instantly logs information when powered on. It also has a CO electrochemical sensor (CO-AF, Alphasense). The data from the PID depends upon the relative response of the VOC detected to the calibration gas, isobutylene, in ppm.

Tenax™ TA sorbent tubes were also used with analysis by TD-GC-MS. The sorbent traps VOCs in the volatility range of 100 – 400℃, n-C_7 to n-C_{26}. The advantage of passive rather than pumped use of the tubes is a longer exposure period and no external power is required during sampling. TD is preferred to solvent desorption/extraction methods due to dilution steps which lower the sensitivity and may interfere in the analysis by overlapping and covering up peaks of interest in the chromatograph. When used, travel blanks are to be taken as a reference.

To have more comparable data to guidelines expressed as mass per unit volume and to the sorbent, the downloaded PID data is converted to a toluene equivalent µg m^{-3} where: 1 ppm isobutylene = 1,889 µg m^{-3} toluene, assuming a temperature of 25ºC (RAE Systems Inc., 2010). The two methods are not equivalent methods as the PID will respond to a different but overlapping range of compounds to that of sorbent tubes.

3.1.4 Particles

Microdust Pro aerosol monitoring system (Casella CEL) was used when available for real time monitoring of particulate concentration in mg m^{-3}. The monitor has a resolution of 0.001 mg m^{-3} with a range of 0.001 – 2500 mg m^{-3}. It measures all particulates that pass through the probe of the logger but is most accurate within the 0 – 10 µm range.

The Microdust Pro measures particles by detection of the scattering of an infra-red source (880 nm). Under clean air conditions all the light is prevented from reaching the detector by a light stop, but when exposed to particles the light is scattered at a narrow angle.

3.1.5 Ultrafine particles

For measurements of UFP, the Model 8525 P-TRAK ultrafine particle counter (UPC), (TSI) was available for use. Its method of operation is described in Section 1.8. A wick is used to supply isopropyl alcohol involved in the detection process and is required to be recharged daily or before each use. The monitor measures particles in the size range of 0.02 – 1 µm with a concentration range of 0 - 5×10^{5} pt cm^{-3}. As the size definition of UFPs is those of 0.1 µm or less, the UPC also measures fine particles in the range of 0.1 – 1 µm. Wallace *et al.,* (2011) used the Model 3007 (TSI) which has a similar range of 0.01 - 1 µm to monitor personal exposure of UFP, they noted that size distributions suggest that UFP usually make up the majority of the particle numbers, and indoor sources typically account for 87 – 98% of freshly created particles. The length of

continuous operation is 8 hours, after which the alcohol wick is required to be replenished, the batteries also limit the length of continuous operation.

3.2 Pilot studies and development of the study protocol

3.2.1 Pilot study homes

A draft protocol for measurement of combustion products in homes was prepared based on studies in the literature review and the published British Standards concerning measurement of indoor air pollutants. The pilot studies focussed on measurements during gas cooking activities and were undertaken prior to the heating season using the draft protocol.

The aim of the pilot studies were to aid the development of the protocol, from experience gained with use of the draft procedure and equipment and feedback from the participants concerning the ease of use and their understanding of the forms. An example of participant's feedback leading to improvement was the inclusion of guidance notes for the questionnaire about the household characteristics, as further explanation was required by some participants for some of the questions. Amendments and suggestions were also made in response to feedback from the Cranfield Health Ethics Committee, such as how data should be stored and how the implications of the results should be conveyed to the participants. The practicality and the suitability of the instruments to measure CO concentrations and other combustion gases typical of that found in kitchens whilst also obtaining data on typical background levels were also assessed.

There were up to four draft forms given to participants, which included instructions for equipment setup and use, activity diaries detailing cooking activity, time spent in the home and windows opened and a questionnaire about the house. While not collected according to the final protocol some of the data is informative with regard to assessing levels of indoor air pollutants.

To recruit participants to the pilot study an email was sent out to colleagues asking for volunteers with gas cookers in their home. A date was arranged for

monitoring over an agreed period of time for those who responded. The participants took the monitors from the laboratory to their home and set them up themselves according to the draft instructions which included information on how to setup the different pieces of equipment and ideal locations for monitors; this was adapted from conditions found to be ideal in the literature review.

Equipment given to the participants varied in the studies; this was due to what was available and practical for the participant. Logging rates for the continuous monitors were also varied on occasion for at least one ICOM CO logger. Table 3-1 summarises characteristics of the five pilot homes (coded H1 to H5); none of the homes were smoking households.

Table 3-1: Characteristics of the five pilot study homes

Property code	Year built / age band	Build type	Main cooking fuel	Main heating fuel	Monitoring equipment used	Location
H1	1945 - 1964	Semi-detached maisonette	Gas	Gas	ICOM	Hertford-shire
H2	1919 - 1944	Semi-detached	Gas / electric	Gas	ICOM, EL	West Midlands
H3	Pre 1900	Detached	Gas / electric	Oil	ICOM, EL, PID, UPC	Bedford-shire
H4	1991 - 1995	Detached	Gas / electric	Gas	ICOM, EL, PID, UPC	Cambrid-geshire
H5	2009	Semi-detached	Gas / electric	Gas	ICOM, EL, Drager tubes, PID, UPC, NO_2 tubes	Bedford-shire

At the end of the monitoring period, the monitors were returned to the laboratory and the monitored data downloaded to a PC and analysed using Microsoft Excel.

The protocol developed consisted of procedures, a study guide, forms and letter templates and these are shown in Appendix D. The main documents are;

- A study protocol agreed by the Cranfield Health Ethics committee.
- An introductory invitation letter to potential participants that was, followed up by provision of further information, including a guide for the monitoring procedure, participant information sheet and consent form. If the participant showed continued interest in taking part, the researcher arranged a time and date for the home visit to explain the monitoring procedure, collect the signed consent form and set out the monitors and agree a time and date for their collection.
- Activity diaries for participants' detailing time spent in different rooms around the home, ventilation used and cooking activities undertaken.
- Questionnaire describing the house and appliances included guidance notes to assist in completing the form.
- Post-study letters to inform participants of their monitoring results and to highlight any issues of concern.

3.2.2 Ethics committee

The full study protocol (Appendix D) was approved by the Cranfield University Health Research Ethics Committee. This process included consultation of what information was required to be provided to the committee and to the participants. After submission of the draft protocol, corrections and suggestions were taken into account before resubmission. Inclusion of a consent form and a participant information sheet which were not included in the first draft of the

protocol and details of how personal data would be stored were among the amendments made.

3.3 Main study and control homes

3.3.1 Recruitment method and monitoring procedure

There were 6 main stages to the recruitment process/monitoring procedure of the study protocol and these are summarised below.

1. House recruitment – The two main approaches used in order to recruit participants for the monitoring were mass letter drops, which included cold calling to discuss the monitoring with potential participants in newly built housing areas, and direct contact with housing associations and local councils to ask for their assistance. In addition working colleagues, friends and family were contacted. All resulted in limited but sufficient success. In the first instance, no compensation was offered for participation but there were concerns about the response rate. This prompted the offer of CO alarms to participants, which incited a slightly more positive response. The offer of a high street voucher to participants was then reviewed by the Cranfield University Health Research Ethics Committee and approved, and was then adopted as a further incentive to get a greater response.

2. Inform the household – if initial contact proved successful, additional information providing further details of the methodology which would be applied, including information about the monitoring equipment, its ideal placement positions, participant information sheets and a consent form.

3. Home visit – a home visit would be arranged if the participant agreed to the terms and signed the consent form which would be collected on the initial home visit. As part of this visit the monitoring equipment would be set out, and forms associated with the monitoring, such as activity diaries, would be handed out and explained. The monitoring procedure followed is described in the study protocol (Appendix D), which also

defined the ideal positioning of monitors, but the occupants would ultimately have to agree to the positioning in order that they would not disrupt the occupant's behaviour. Essentially it involved the monitoring of CO over two days ideally in three locations; the kitchen, living room and bedroom. Passive NO_2 tubes would also be set out for two weeks. Where possible (equipment availability permitting) particles, UFPs and VOCs would also be monitored over the main two days of monitoring. The activity diaries were to be completed over the two days primarily by the main participant with regards to the cooking, ventilation and burning of candles or occurrence of smoking and solely by the main participant when detailing the amount of time spent around the home in different rooms.

4. Collection of monitors – during the initial home visit, a time for the collection of the monitoring equipment and the associated forms would be arranged (usually 2 days later if possible). Diffusive tubes were usually exposed for 2 weeks, and these would be posted back using the self-addressed envelope provided, and this action was prompted by email or telephone if requested by the participant.

5. Obtain and analyse results – the data for the electronic monitoring equipment was uploaded to a computer and analysed, and the diffusive tubes were analysed by an appropriate method and results evaluated.

6. Inform the household of results – the participants were informed of their monitoring results regarding comparison to health based guidelines for CO and NO_2. Templates for these letters were created (Appendix D), and three scenarios were distinguished: one where pollutant concentrations were below WHO guidelines, one where pollutant concentrations were above WHO guidelines and a third where CO concentrations were above workplace exposure limits.

Two types of homes were monitored during the heating season, the main study energy efficient homes, built or refurbished from 2007, and the control homes,

which were older homes, built to older Building Regulation standards and therefore to lower standards of energy efficiency.

3.3.2 Main study and control homes information

Data from the questionnaire that participants of the study completed (Appendix D-14) on the occupation and characteristics of the property is summarised in Table 3-2 and data on the insulation and appliances is summarised in Table 3-3 for the energy efficient homes monitored in the main study. Data for the control homes monitored according to the full study protocol are summarised in Tables 3-4 and 3-5 using information from the property questionnaire. To distinguish homes from one another whilst retaining personal details, no names or address were to be stored on a computer and homes were coded by letters (e.g. Home MK1), where the code would only be known by the researcher and supervisor.

(N.B. TW1 had a major refurbishment in 2010. Homes MK2, MK3 and MK4 are on the same housing estate and CH1 and CH2 are both on a different housing estate. MK6 and MK7 are in the same block of flats and on the same estate as MK8).

Table 3-2: Occupants and property information for main study homes

	MK1	MK2	MK3	MK4	MK5	MK6	MK7
Year built	2010	2010	2007	2007	2007	2009	2009
Built form	Semi-detached	End terrace	End terrace	Semi-detached	1st floor flat	2nd floor flat	1st floor flat
Location	Suburban - light traffic	Suburban - light traffic	Suburban - light traffic	Suburban - light traffic	Suburban - moderate traffic	Urban – moderate traffic	Urban – moderate traffic
Levels	2	3	2	2	2	1	1
Rooms:							
Kitchen	1	1	1	1	1	1	1
Bedroom	3	3	3	3	1	2	2
Living room	1	2	1	1	1	1	1
Utility room	-	1	1	1	-	-	-
Basement	-	-	-	-	-	-	-
Conservatory	-	-	-	-	-	-	-
WC/bathroom	2	2	1	2	1	2	2
Other	-	1	-	-	1	-	-
Attached/integral garage	No	No	No	No	No	Integral	Integral
Smoking household?	No	No	No	No	No	No	No
Candles / incense burnt?	Yes	No	No	No	No	No	Yes
Occupant age:							
0-5	-	1	-	1	-	-	-
5-16	2	-	-	-	-	2	-
17-65	1	2	-	2	2	1	1
65+	-	-	1	-	-	-	-

	MK8	MK9	TW1	CH1	CH2	LB1	WS1
Year built	2010	2008	1945 – 1964	2009	2010	2008	2007
Built form	3rd floor flat	Ground floor flat	Semi-detached	Semi-detached	1st floor flat	2nd floor flat	Mid-terrace
Location	Urban – moderate traffic	Urban – light traffic	Suburban - moderate traffic	Rural - light traffic	Rural - light traffic	Suburban-moderate traffic	Suburban-light traffic
Levels	1	1	2	2	1	1	3
Rooms:							
Kitchen	1	1	1	1	1	1	1
Bedroom	2	2	3	3	1	2	4
Living room	1	1	1	1	1	1	1
Utility room	-	-	-	-	-	-	-
Basement	-	-	-	-	-	-	-
Conservatory	-	-	-	-	-	-	-
WC/bathroom	1	1	1	3	1	2	4
Other	-	-	-	-	-	-	1
Attached/integral garage	Integral	No	No	No	No	No	No
Smoking household?	No	No	No	No	No	No	No
Candles / incense burnt?	Yes	No	Yes	No	Yes	Yes	No
Occupant age:							
0-5	-	-	2	-	-	-	-
5-16	-	-	2	-	-	-	-
17-65	1	2	2	1	2	2	1
65+	-	-	-	-	-	-	1

Table 3-3: Insulation and appliance information for main study homes

	MK1	MK2	MK3	MK4	MK5	MK6	MK7
Glazing and frame type	Double – wood	Double - wood	Double - wood	Double - wood	Double - plastic	Double – wood	Double - wood
Trickle ventilators	Yes – all	Yes – all	Yes – all	Yes – all	No	No	No
Wall Type	Insulated cavity	Insulated timber – frame			Insulated cavity		
Ground level floor type	Don't know	Insulated suspended chipboard			Don't know	Concrete beams / blocks	
Main heating fuel & type	Gas – central heating						
Appliance location and age	Exterior ~1 year	Bathroom ~1 year	Bathroom ~3 years	Bathroom ~3 years	Cupboard ~3 years	Kitchen ~2 years	Kitchen ~2 years
Flue/chimney	Flue	Flue	Flue	Flue	Flue	Flue	Flue
Secondary heating fuel & type	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Primary cooking appliance	Gas – hobs	Gas – hobs	Gas – hobs	Gas – hobs	Electric – oven/grill/ hobs	Gas – hobs	Gas – hobs
Secondary cooking fuel	Electric – oven/grill	Electric – oven/grill	Electric – oven/grill	Electric – oven/grill	N/A	Electric – oven/grill	Electric – oven/grill
Cooker age	~ 1 year	~ 1year	~3 years	~3 years	~3 years	~2 years	~2 years
Cooker hood type	Extract to outside	Re-circulates	Re-circulates	Re-circulates	Extract to outside	Extract to outside	Extract to outside
Pilot light	No	No	No	No	No	Yes	Yes
	MK8	MK9	TW1	CH1	CH2	LB1	WS1

Glazing type	Double - wood	Double – Plastic	Triple - Plastic	Double – Plastic	Double - Plastic	Double – not stated	Double – Plastic
Trickle ventilators?	No	No	No	Yes – all	Yes - some	No	Yes – some
Wall Type	Insulated cavity			Don't know	Insulated cavity		
Ground level floor type	Concrete beams/blocks	Solid floor	Insulated concrete beams/blocks			Don't know	Solid floor
Main heating fuel & type	Gas – central heating					Electric – individual radiators	Gas – central heating
Appliance location and age	Cupboard ~1 year	Flat corridor ~ 3 years	Bedroom ~1 year	Kitchen ~1 year	Cupboard ~1 year	Each room ~3 years	Kitchen ~3 years
Flue/chimney	Flue	Flue	Flue	Flue	Flue	N/A	Flue
Secondary heating fuel & type	N/A	N/A	Biomass single stove	N/A	Electric portable heater	N/A	Electric fire
Location and age	N/A	N/A	Living room <1 year	N/A	-	N/A	Living room ~3 years
Flue/chimney	N/A	N/A	Chimney	N/A	N/A	N/A	N/A
Primary cooking appliance	Gas – hobs	Electric – oven/ grill/ hobs	Gas – hobs	Gas – hobs	Gas – hobs	Electric – oven/ grill/ hobs	Gas – hobs
Secondary cooking fuel	Electric – oven/grill	N/A	Electric – oven/grill	Electric – oven/grill	Electric – oven/grill	N/A	Electric – oven/ grill
Cooker age	-	~3 years	~1 year	~1 year	~1 year	~3 years	~3 years
Cooker hood type	Extract to outside	Extract to outside	Re-circulates	Extract to outside	Re-circulates	Extract to outside	Extract to outside
Pilot light	No	No	Yes	No	No	No	No

Table 3-4: Occupants and property information for control homes

	SA1	SA2	WV1	WV2	CC1
Age Band	1965-1975	1919-1944	1919-1944	1965-1975	1995-1997
Built form	Semi-detached	Semi-detached	Semi-detached	Detached	Detached
Location	Suburban - light traffic	Rural – moderate traffic	Urban – moderate traffic	Suburban – light traffic	Suburban – light traffic
Levels	2	2	2	2	2
Rooms:					
Kitchen	1	1	1	1	1
Bedroom	3	5	3	3	3
Living room	1	1	2	1	1
Utility room	-	-	1	1	-
Basement	-	-	-	-	-
Conservatory	1	-	-	-	2
WC/bathroom	2	2	2	1	3
Other	-	1	-	2	1
Attached/integral garage	No	Integral – no motor vehicle stored	Attached – no motor vehicle stored	Attached – car stored inside	No
Smoking household?	No	No	No	No	No
Candles / incense burnt?	Yes	No	Yes	No	No
Occupant age:					
0-5	-	-	-	-	-
5-16	-	-	-	-	-
17-65	-	2	5	3	2
65+	1	-	-	-	-

Table 3-5: Insulation and appliance information for control homes

	SA1	SA2	WV1	WV2	CC1
Glazing type	Double	Double	Double	Double	Double
Glazing frame	Plastic	Plastic	Plastic	Plastic	Plastic
Trickle ventilators?	No	Yes – some	No	No	Yes – all
Wall Type	Insulated cavity	Solid	Don't know	Don't know	Insulated cavity
Ground level floor type	Solid floor	Solid floor – kitchen floor only Suspended timber	Un-insulated suspended timber floor	Un-insulated solid floor	Insulated solid floor
Main heating fuel & type	Gas -central heating	Gas -central heating	Gas -central heating	Gas -central heating	Gas -central heating
Appliance age	~20 years	~14 years	~12 years	25+ years	Don't know
Appliance location	Airing cupboard	Living room	Kitchen	Garage	Kitchen
Flue/chimney?	Flue	Flue	Flue	Flue	Flue
Secondary heating fuel & type	Individual gas radiator	Single gas stove	Gas heater	Individual electric radiators	Individual electric radiator
Age	~20 years	~7 years	15+ years	5+ years	~ 1 year
Location	Living room	Dining room	Living room	Utility room	Conservatories
Flue/chimney?	Flue	Chimney	Chimney	N/A	N/A
Primary cooking appliance-	Gas– oven/grill/hobs	Electric – oven/grill/hobs/ microwave	Gas – oven/grill/hobs	Gas – oven/grill/hobs	Gas – hobs
Secondary cooking fuel	Electricity – microwave	N/A	Electricity – microwave	N/A	Electric – oven/grill
Cooker age	~5 years	~20 years	>10 years	~10 years	~15 years
Cooker hood type	No	Extract to outside	Extract to outside	No	Extract to outside
Pilot light?	No	No	No	No	Yes

UFPs and VOCs were not always monitored in all of the homes; this was either due to technical difficulties or difficulty in obtaining the instruments for the required periods. Table 3-6 shows the various types of monitoring equipment used in the main study homes, in addition to the CO monitors and NO_2 tubes. As four CO monitors were available for the majority of the study and three essential locations identified for the monitoring, two monitors were placed in different appropriate locations in the kitchen as this was generally where combustion products would most likely be detected.

Table 3-6: Additional monitoring equipment used in the main study (excluding CO and NO_2 monitors)

Property code	Additional equipment used	Property	Additional equipment used
MK1	UPC	MK8	UPC, PID
MK2	UPC	MK9	UPC, PID
MK3	-	WS1	PID
MK4	UPC	CH1	UPC
MK5	UPC	CH2	UPC, Tenax tubes (VOC)
MK6	UPC, PID	TW1	UPC, Tenax tubes (VOC)
MK7	UPC	LB1	UPC

Table 3-7 shows the additional combustion pollutants monitored in the control homes.

Table 3-7: Additional monitoring equipment used in the control study homes (excluding CO and NO_2 monitors)

Property code	Additional equipment use
SA1	UPC, PID
SA2	UPC, particle monitor, PID
WV1	UPC, particle monitor
WV2	PID
CC1	UPC, PID

3.4 Modelling

Modelling is used in the study to complement the measurement programme to assess the risks to health of CO in energy efficient homes. The model is required to simulate scenarios assuming variables such as the air exchange rate and room dimensions, and source rate to determine for which parameters and over what period of time CO levels in the modelled room would be deemed harmful to human health by comparison to indoor air guidelines. Modelling allows exploration of various input scenarios and prediction of how these inputs may impact on health.

For the modelling in this project the focus is on CO as, of the various pollutants generated from indoor sources of combustion, it poses the greatest risk to health. The main model selected for use was the INDAIR C++ because its ease of use and ability to model the multiple rooms typically most occupied in the home and therefore the most important with regards to exposure. It has also been previously used for similarly exploring CO concentrations in the home (Dimitroulopoulou *et al*., 2006)**.** The modelled scenarios focus on indoor

sources of CO, the outdoor concentrations will be assumed to be negligible and input as 0 ppm. To simplify the modelling, although other sources of combustion and other rooms may have sources, just the kitchen using the cooker as a source is explored. The dimensions of the rooms used in the model were taken from an eco-home estate, where some homes were monitored as part of the main study. The living room, kitchen and bedroom had dimensions of 3.4m x 3.6m x 2.3m, 3.4m x 2.7m x 2.3m and 3.4m x 3.0m x 2.3m respectively.

3.4.1 INDAIR C++

INDAIR C++ is a mass-balance model where indoor concentrations can be calculated as a function of indoor sources, outdoor concentrations and building and pollutant characteristics, such as the transport of air pollutants between rooms and the outdoor environment. This model has various inputs which can be altered to model various scenarios. It models 3 rooms: the kitchen, the living room and the bedroom. These 3 rooms are deemed to be the most important homes in the house regarding exposure to pollutants due to the time spent in them and the sources, such as kitchen appliances. The air exchange rates (h^{-1}) between these rooms can be set as well as the individual room to outdoor air exchange rate. The surface area (m^2) of the floors and walls as well as the volume (m^3) of the rooms is also a variable input. For each room a source (mg s^{-1}) from cooking and smoking can be set for the following combustion generated air pollutants: CO, NO_2, PM_{10} and $PM_{2.5}$. As the model calculates lognormal distributions it does not calculate zero or negative values correctly, so zero or negative values are to substituted with a very small number close to zero e.g. 1.00×10^{-40}. The input file for the model is set so that the sources can be changed every 15 minutes for 24 hours. The files can be outputted to give 15 minute intervals of the data as well as intervals of hourly and 24 hour estimated averages. The outputted pollutants are given in various units, CO ppm, NO_2 ppb and PM_{10} and $PM_{2.5}$ µg m^{-3}.

For the modelled data, it is assumed that the cooker hood is turned off during the cooking period. Two main types of scenarios were established to explore:

'worst case' scenarios and 'normal' scenarios. For both types, multiple simulations are run with varying emission rates for kitchen CO and varying ventilation rates for internal and external air exchange. The 'worst case' scenarios are used to explore air tight structures, these include low air exchange that may occur due to poor performance or improper use of mechanical ventilation. The 'normal' scenarios include consideration of moderately low emission rates combined with a range of ventilation rates, as well as the high emission rates combined with higher ventilation rates.

3.4.2 Single-compartment mass-balance model

Using Equation 3-1, the concentration of a pollutant can be calculated for a single room or chamber of a set volume. Using this model, the concentration can be derived assuming perfect mixing and is derived by taking account of mass flows of the gas within the room. The model can be used for a range of pollutants and the removal rate of gas due to sorption (k) can be altered to adjust for this. For CO, it is assumed that k = 0. The units given in Equation 3-1 are just example units, and can be changed if the units are kept consistent, for example the concentration can be calculated in µg m^{-3} if the concentration in the room is input as µg m^{-3} and the room volume is input in m^3.

Equation 3-1: Single box concentration

$$C = A + (C_I - A).\exp[-(Q + k)]t$$

C = Concentration of the gas inside of the room (mg m^{-3})
A = (Q.Co+S/V)/(Q+k)
Q = Air exchange rate (h^{-1})
Co = Concentration of the gas outside of the room (mg m^{-3})
S = Source release rate (mg h^{-1})
V = Volume of the room (m^3)
k = The removal rate of gas due to sorption effects in the room (h^{-1})
Ci = Initial gas concentration indoors (mg m^{-3})
t = Time (h)

Altering t, this can be used in a spread sheet to plot a chart to show the trend of the pollutant being modelled. Rearranging the equation can also give a formula to work out source rate from observed concentrations (Equation 3-2), this

formula assumes that the pollutant has reached equilibrium with the environment at t = ∞, simplifying the concentration to C = A. This can give an approximation for a concentration in a known room size, but equilibrium will never be reached in a real environment as conditions are not stable and source rates are not constant.

Equation 3-2: Equation to calculate source rate derived from Equation 3-1, assuming concentration has reached equilibrium with the environment

$S = V [C (Q + k) – Q.C_O]$

Equation 3-3 can also be used to determine emission rates, using the maximum concentration observed, the time the source was on and an appropriate mixing volume such as the whole first floor for cooking or the volume of the kitchen (Wallace and Ott, 2011).

Equation 3-3: Equation to calculate emission rate (Wallace and Ott, 2011)

$S = (C_{max} V) / t$

S = emission rate (pt min^{-1})
C_{max} = maximum concentration (pt cm^{-3})
T = time (min)
V = mixing volume (cm^3)

Other useful information that could be required to be estimated from data for use in modelling is air exchange rate, which can be calculated using Equation 3-4, using the concentration of a gas over two points in time tracing its decay. This is taken from a British Standard used to estimate mean air exchange rate using a tracer gas (British Standards Institution, 2001c).

Equation 3-4: Calculation of mean air exchange (British Standards Institution, 2001c, Pg 8)

$n_{av} = \ln C(t_1) - \ln C(t_1) / (t_2 – t_1)$

n_{av} = mean air exchange rate (h^{-1})
$C(t_1 / t_2)$ = concentration at time 1 / time 2
$t_{1 / 2}$ = time period 1 / 2 (h)

4 Results

4.1 Pilot study homes

Table 4-1 summarises the results obtained for the five pilot study homes used for monitoring CO. None of the WHO indoor air guidelines were exceeded. The full results are shown in Appendix C.

Table 4-1: Maximum time weighted averages for CO in pilot study homes

Property code	Main cooking fuel	Maximum 15 minute CO average (ppm)	Maximum 1 hour CO average (ppm)	Maximum 8 hour CO average (ppm)	Maximum 24 hour CO average (ppm)
H1[a]	Gas	4.4	4.3	N/A	N/A
H2[b] P1 P2	Gas / electric	 5.7 8.6	 2.6 6.0	 0.7 2.3	 0.5 1.3
H3	Gas / electric	0.4	0.3	0.2	0.2
H4	Gas / electric	8.0	4.4	1.5	1.1
H5	Gas / electric	0.5	0.4	0.3	0.3

[a] H1 was monitored for less than 2 hours, so no 8 / 24 hour data available

[b] H2 was monitored on two occasions, monitoring periods 1 (P1) and 2 (P2)

The logging rates for the EL had to be varied from the ICOMs, which were usually set at 1 minute logging intervals, as any other logging rate used other than 10 seconds did not seem to obtain useful readings. The 10 second logging

rate for the EL was found to work better in tests, and the observed concentrations at this logging rate correlated well with the ICOM. Higher average and peak CO concentrations were found in the two homes which have gas fuelled ovens as opposed to electric.

In H2 the average of the ICOM in P1 was 0.4 ppm over the 38 hour period whereas the two EL average readings for this time were 0 ppm and 3 ppm. In P2 an average CO reading from the ICOM of 1.1 ppm and the two EL average readings for this time were 0 ppm and 3.6 ppm. EL 1 only showed a response when the cooking grill was used, and elevated levels were observed with the peak values observed from the gas grill used in H2. EL 1 only read a maximum of 1.5 ppm at the same time when the ICOM was reading 7.3 ppm. In H2 use of the gas grill coincided with peaks in CO, the maximum peak found was that of 11.5 ppm, the highest peak out of the five homes.

For H2, the activity diary was not handed out during the first monitoring period. It was available for the second period, but the participant did not fill in the diary completely for the first day, and did not fill in the diary at all on the second day. This suggested that the diary may need to be simpler to try and ensure that participants will complete this form. Generally, the peaks in CO observed in the kitchen are associated with periods of gas cooking except in H3 where use of the gas hob did not seem to affect levels of CO.

During these pilot studies, passive diffusive NO_2 and CO monitors shown in the list of equipment in Appendix D were only used once. As these tubes are smaller than the other equipment, they could be useful for monitoring closer to the source to observe a worst case scenario of exposure that people may experience in their home, but a limitation arises with this method as these tubes only give the average concentration for the period that they are exposed and peaks would not be observed. As the monitors were given to the participants to place out themselves, the placement of the monitors may have affected readings compared to when a researcher places the monitors.

All CO monitored was low in comparison to WHO indoor air quality guidelines and only peaks reached or exceeded the 8 hour average of 9 ppm for brief periods of time, but did not exceed this over an averaged 8 hour period. It is also worth noting that the EL monitors have lower resolution than the ICOM, and therefore does not detect the low ambient and background levels which can be monitored with the ICOM when co-located.

4.2 Main study homes

As part of the main study a total of 14 homes built or retrofit since 2007 were monitored according to the protocol (Appendix D). None of the 14 homes monitored for the main part of the study were smoking households. Selected characteristics of the properties are summarised in Table 4-2, along with selected pollutant data from the kitchen; average NO_2, average CO concentrations (from the ICOM) and the maximum CO (from either monitor in the kitchen).

Table 4-2: Selected characteristics of homes monitored in the main study and CO and NO_2 data monitored in their kitchens

Property code	Year built / age band	Main cooking fuel	Main heating fuel	Average CO (ppm)	Maximum CO (ppm)	Average NO_2 (µg m^{-3})
MK1	2010	Gas / electric	Gas	0.8	13.9	9.2
MK2	2010	Gas / electric	Gas	0.7	10.7	11.2
MK3	2007	Gas / electric	Gas	0.5	1.7	17.1
MK4	2007	Gas / electric	Gas	0.5 / 1.3*	4.8 / 2.0*	11.9 / 14.4*

MK5	2007	Electric	Gas	0.9	1.6	12.0
MK6	2009	Gas / electric	Gas	1.5	1.9	12.2
MK7	2009	Gas / electric	Gas	1.3	2.1	9.2
MK8	2010	Gas / electric	Gas	1.5	2.6	5.9
MK9	2008	Electric	Gas	0.8	1.3	3.4
CH1	2009	Gas / electric	Gas	0.7	7.5	18.3
CH2	2010	Gas / Electric	Gas	1.0	8.5	12.9
TW1	1945-1964 Retrofit 2010/11	Gas / electric	Gas	1.1	7.3	22.8
LB1	2008	Electric	Electric	0.8	1.7	12.3
WS1	2007	Gas / electric	Gas	1.1	5.9	23.7

*MK4 was monitored in two different monitoring periods

None of the main study homes relied on gas solely as a fuel for cooking, 12 of the 14 homes had gas hobs and an electric oven and the other two had both electric hobs and ovens. For heating, only one home was not fuelled by gas, and this was fuelled by electricity.

Table 4-3 summaries data on cooking, ventilation and time spent around the home from the activity diaries filled out by participants of the main study homes

over the two main days of monitoring (excluding the period where passive diffusive tubes were used). Further information detailing data for each pollutant by house and room is given in Appendix E.

Table 4-3: Cooking activities, time spent around the home and opening of windows for the main study homes

House code	Number of cooking activities	Number of times cooker hood used (speed setting)	Approximate time spent in the home (room where majority of time spent in)	Approximate time of windows opening in the home
MK1	5	1 (med)	88% (kitchen)	Shut throughout
MK2	4	4 (2 low, 1 med, 1 high)	94% (bedroom)	6%
MK3	3	0	92% (kitchen)	Shut throughout
MK4 P1 MK4 P2	3 1	0 2 (1 low, 1 med)	100% (living room) 72% (living room)	Shut throughout 3%
MK5	4	0	94% (bedroom)	10%
MK6	-	-	67% (bedroom)	10%
MK7	2	1 (low)	31% (bedroom)	Shut throughout
MK8	3	1	74% (living room)	Shut throughout
MK9	2	0	69% (living room)	1%
CH1	2	0	58% (bedroom)	Not filled in

CH2	4	2 (low)	77% (living room)	Shut throughout
TW1	2	2 (low)	62% (living room)	16%
WS1	3	1 (low)	88% (living room)	100%
LB1	2	0	58% (bedroom)	Shut throughout

*med = medium

4.2.1 Carbon Monoxide

Table 4-4 shows time weighted average concentrations of CO for comparison to the WHO indoor air guidelines (15 minute, 1 hour, 8 hour and 24 hour). Monitors were set out according to the protocol; the monitor in the kitchen with the highest resolution (ICOM) was used for the data in Table 4-4.

Table 4-4: Main study homes summarised data for kitchens for CO: CO maximum averages for 15 minute, 1 hour, 8 hours and 24 hours

House	Maximum 15 minute CO average (ppm)	Maximum 1 hour CO average (ppm)	Maximum 8 hour CO average (ppm)	Maximum 24 hour CO average (ppm)
MK1	10.5	5.8	2.0	1.9
MK2	7.1	3.7	1.1	0.8
MK3	1.5	1.3	0.8	0.6
MK4*	2.6 / 1.7	1.5 / 1.7	0.8 / 1.5	0.8 / 1.3
MK5	1.5	1.5	1.1	1.0
MK6	2.1	2.1	1.9	1.9
MK7	2.3	2.3	2.0	1.8

MK8	3.5	3.3	2.8	2.8
MK9	1.3	1.3	1.1	0.8
TW1	6.4	4.2	1.5	1.5
WS1	3.2	3.2	2.8	2.8
CH1	7.4	6.3	2.0	0.8
CH2	5.6	3.6	1.4	1.2
LB1	1.6	1.6	1.4	1.4

*two sampling periods

Table 4-5 presents the average CO by room for the main study homes. It includes both monitoring periods in MK4, hence n = 15 not 14. From Table 4-5, the average over the 2 day monitoring period for the bedrooms of the main study homes ranged from 0 – 1.4 ppm, the living room averages ranged from 0 – 2.5 ppm and the kitchens 0.5 – 1.5 ppm.

Table 4-5: Average CO concentration by room (2 day measurement period in each home)

Rooms	CO (ppm) - Main study homes, n = 15
Kitchen – average	1.0
Standard deviation	0.3
Range	0.5 - 1.5
Living room – average	0.9
Standard deviation	0.8
Range	0.0 - 2.5
Bedroom – average	0.3
Standard deviation	0.4
Range	0.0 - 1.4
Indoors – average	0.8
Standard deviation	0.6

There was no significant difference in CO between the kitchen and the living room ($t = 0.65$, $df = 26$). The average difference in concentration between the kitchen and the living room in each home was 0.5 ppm (95% confidence interval = 0.32 - 0.68), the standard error of the mean (SEM) was 0.091. There was a significant difference between the kitchen and the bedroom ($t = 4.47$, $df = 26$) and the living room and the bedroom ($t = 2.25$, $df = 25$). The average difference between the kitchen and the bedroom was 0.7 ppm (95% confidence interval = 0.49 - 0.91) and the SEM was 0.105. The average difference between the living

room and the bedroom was 0.8 ppm (95% confidence interval = 0.42 - 1.18) and the SEM was 0.192.

4.2.2 Nitrogen dioxide

Table 4-6 presents the average NO_2 concentration measured by diffusive samplers in each room for the main study homes. There was no significant difference between the kitchen and the living room (t = 1.35, df = 26) and the living room and the bedroom (t = 1.23, df = 26). The average difference between the kitchen and the living room was 2.8 µg m^{-3} (95% confidence interval = 0.72 – 4.88) and the SEM was 1.060. The average difference between the bedroom and living room was 2.9 µg m^{-3} (95% confidence interval = 1.69 – 4.11) and the SEM was 0.617. There was a significant difference between the kitchen and the bedroom (t = 2.53, df = 28). The average difference between the kitchen and the bedroom was 5.1 µg m^{-3} (95% confidence interval = 2.62 – 7.58) and the SEM was 1.267 (as two values for the living room were missing, when calculating the average differences, values of the average for that room had been used to fill in that data).

Table 4-6: NO_2 concentration by room

Rooms	NO_2 (µg m^{-3}) - Main study homes, n = 15
Kitchen – average	13.1
Standard deviation	5.6
Range	3.4 – 23.7
Living room – average	10.4
Standard deviation	4.7
Range	2.6 – 21.3
Bedroom – average	8.1
Standard deviation	5.2
Range	2.6 – 23.7
Indoors – average	10.6
Standard deviation	5.5

(Note: MK2 and CH2 did not have NO_2 monitored in the living room. N = 15 for the main study homes as MK4 was monitored twice).

4.2.3 Ultrafine particles

Table 4-7 summarises average and maximum concentrations and activities that occurred during the operation of the UPC in each main study home.

Table 4-7: Average and maximum levels of UFP in the kitchens of the main study homes

House	Average UFP (pt cm^{-3})	Maximum UFP (pt cm^{-3})	Activities
MK1	5,008	7,360	None
MK2	46,103	500,000	Gas cooking before monitoring
MK4	56,382	154,900	Cooking (electric)
MK5	119,075	315,683	Cooking (electric)
MK6	48,026	451,765	Gas cooking before monitoring
MK7	105,417	500,000	Cooking (electric)
MK8	24,359	172,833	Cooking (gas)
MK9	13,516	43,135	Electric cooking before monitoring
CH1	40,109	391,167	Cooking (gas)
CH2	112,084	493,100	Cooking (gas)
TW1	4,160 (4,616)*	17,198 (18,480)*	Cooking (gas)
LB1	45,795	373,416	Cooking (electric), candles

*also monitored in the living room of TW1, simultaneously to the kitchen

The collated UFP data for the main study homes is summarised in Table 4-8; 12 of the 14 main study homes were monitored.

Table 4-8: Average data for UFP of the main study and control homes

Kitchen	UFP (pt cm^{-3}) - Main study homes, n = 12
Average	51,670
Standard deviation	40,399
Range	4,160 – 119,075

4.2.4 VOCs

Table 4-9 shows the TVOC concentrations and activities that occurred in the main study homes when the PID was operated.

Table 4-9: Average and maximum TVOC concentrations monitored by PID for main study homes

House	Average TVOC (µg m^{-3})	Maximum TVOC (µg m^{-3})	Activities
MK6	386	1,631	Gas cooking before monitoring
MK7	253	2,799	Cooking (electric)
MK8	549	2,420	Cooking (gas)
MK9	2,134	12,331	Electric cooking before monitoring
WS1	1	332	Gas hobs

Table 4-10 shows the TVOC levels from CH2 and TW1 in the bedroom, living room and kitchen monitored passively over approximately 2 weeks with Tenax TA tubes. Decamethylcyclopentasiloxane (DMCPS) was the only significant

VOC compound identified in both homes as major components of the TVOC The other abundant VOCs for these homes can be found in Appendix E.

Table 4-10: TVOCs analysed by TD-GC-MS in CH2 and TW1 using Tenax TA passive diffusive tubes over two weeks

House	Bedroom average TVOC (µg m^{-3})	Living room average TVOC (µg m^{-3})	Kitchen average TVOC (µg m^{-3})
CH2	276	209	245
TW1	1416	941	743

As an example of the data obtained in each home, detailed results for one home (MK1) are provided and data for each of the other monitored homes are provided in Appendix E. Appendix G describes further investigations monitoring combustion pollutants in and around homes and various other locations where specific activities such as burning incense, use of aerosols and other activities were monitored.

4.3 Detailed monitoring results in property MK1

The monitoring was for approximately 2 days and for both days all windows and external doors for ventilation were shut. The majority of time spent around the house (by the main occupant), during the monitoring period was recorded in the activity diary as being in the home (over 40 of the 48h). The kitchen and the bedroom were the rooms where most of this time was spent. The householder noted that the trickle ventilators were open 24/7. During the first day of monitoring the only cooking activity was brief use of the microwave. During the second day of monitoring the oven was used on two separate occasions and the hobs were used on three separate occasions, five candles were also lit in the kitchen.

4.3.1 Carbon monoxide

Both of the ELs did not log any values above 0 ppm for CO, the two units of these were situated in the living room and in the bedroom. The two ICOMs were both in the kitchen, with one adjacent to the cooker on a work surface and the other on top of a fridge. The data is summarised in Table 4-11. The gas hobs were used numerous times for the cooking activities. The household had a gas boiler, the use of this was not expected to affect readings as it was situated outside. On two separate periods, one hob was used for approximately 15 minutes and the CO rose slightly, but was below 5 ppm for both these occasions. The cooker hood was not used on either of these occasions. The maximum was observed during a cooking activity.

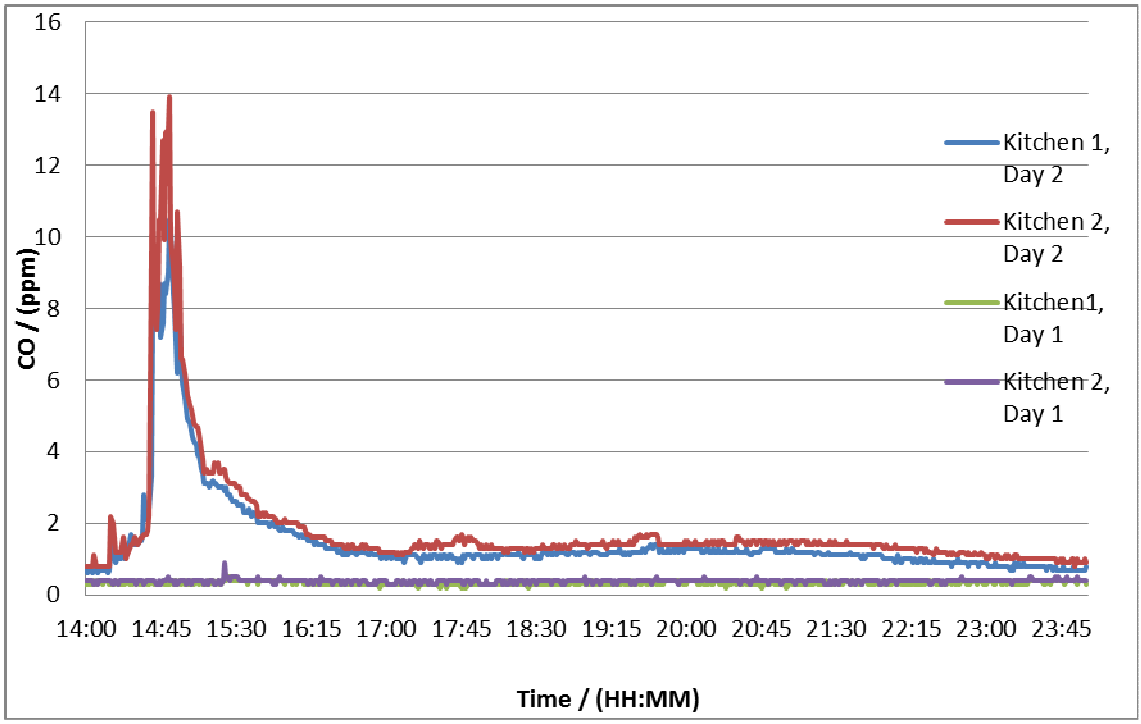
Table 4-11: CO data from kitchen of MK1

	Kitchen 1	Kitchen 2
Maximum	10.5 ppm	13.9 ppm
Minimum	0.2 ppm	0.3 ppm
Average	0.7 ppm	0.8 ppm
Standard deviation	0.9 ppm	1.1 ppm

On the second day of monitoring, one hob was used for approximately 35 minutes, and for 15 minutes of this period the cooker hood was set on medium towards the end of cooking, and was left on for a further 10 minutes. It was during this period that the peak CO for both monitors in the kitchen occurred. Figure 4-1 shows an 8 hour time period for both ICOMs on day 1 and day 2 of the monitoring, which includes the cooking period. On day 1 there was no reported activities in the kitchen and the level was low and this was the general background for the kitchen when no activity had occurred. The cooking started at around 14:20 - 14:55 and the cooker hood was turned on at around 14:40 - 15:05. From 5pm until midnight on the second day, five candles were reported

to be burnt. The CO does not exceed 1.5 ppm for this period, but there may be an affect by the earlier cooking event. After use of the cooker, the level of CO did not decline to the background level observed on day 1 during the 8 hours of monitoring shown in Figure 4-1.

Figure 4-1: 8 hour time data from CO in the kitchen of MK1



4.3.2 Ultrafine particles

The UPC ran for 7.5 hours. This was during the first day of monitoring and no cooking activities coincided with the operation of the UPC. A summary of the recorded UFP levels can be found in Table 4-12.

Table 4-12: Summary of UFP in MK1

	UFP (pt cm^{-3})
Maximum	7,360
Minimum	1,500
Average	5,008
Standard Deviation	683

4.3.3 Nitrogen dioxide

The NO_2 tubes were exposed for 15 days (Table 4-13). The laboratory report from the external laboratory where the NO_2 tubes were analysed can be found in Appendix F.

Table 4-13: Average NO_2 levels over 15 day's exposure in MK1

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	363	9.2
Living room	363	7.8
Bedroom	363	2.8

4.4 Control homes

Five older control homes were monitored according to the study protocol. Selected characteristics of the properties are summarised in Table 4-14, along with selected pollutant data from the kitchen; average NO_2, average CO concentrations (from the ICOM) and the maximum CO (from either monitor in the kitchen). The control homes were built before the main study homes (except TW1, which was an older conventional build originally, though recently a retrofit home), none of the controls were smoking households.

Table 4-14: Main characteristics of control homes monitored and CO and NO_2 data monitored in their kitchens

Property	Year built / age band	Main cooking fuel	Main heating fuel	Average CO (ppm)	Maximum CO (ppm)	Average NO_2 (µg m^{-3})
SA1	1965-1975	Gas	Gas	1.7	57.6	25.1
SA2	1919-1944	Electric	Gas	0.8	2.1	13.9
WV1	1919-1944	Gas	Gas	1.2	11.5	35.3
WV2	1965-1975	Gas	Gas	1.0	14.2	73.3
CC1	1995-1997	Gas/ electric	Gas	12.3	0.9	18.8

All five control homes had gas central heating, three of the five homes were solely gas powered with regards to cooking fuel, with one solely electric and the fifth had gas hobs and an electric oven. Table 4-15 summaries data on cooking, ventilation and time spent around the home from the activity diaries filled out by participants (excluding the period where passive diffusive tubes were used).

Table 4-15: Cooking activities, time spent around the home and opening of windows for ventilation for the control homes

House	Number of cooking activities	Number of times cooker hood used (speed setting)	Approximate time spent in the home (room where majority of time spent in)	Approximate time of windows opening in the home
SA1	1	N/A	83% (bedroom)	Not filled in
SA2	3	2 (1 low, 1 med)	94% (bedroom / living room)	22%
WV1	6	0	Not filled in	Not filled in
WV2	3	N/A	100% (living room)	Shut throughout
CC1	3	3 (high)	100% (bedroom)	Shut throughout

4.4.1 Carbon monoxide

Table 4-16 shows time weighted average concentrations of CO for comparison to the WHO indoor air guidelines (15 minute, 1 hour, 8 hour and 24 hour). Monitors were set out according to the protocol; the monitor in the kitchen with the highest resolution (ICOM) was used for the data in Table 4-16.

Table 4-16: Control homes summarised data for kitchens for CO: CO maximum averages for 15 minute, 1 hour, 8 hours and 24 hours

House	Maximum 15 minute CO average (ppm)	Maximum 1 hour CO average (ppm)	Maximum 8 hour CO average (ppm)	Maximum 24 hour CO average (ppm)
SA1	46.0	21.4	3.9	1.9
SA2	2.1	2.0	1.4	1.2
WV1	8.8	7.2	2.1	2.1
WV2	10.2	5.1	1.4	1.4
CC1	9.2	6.6	1.8	1.4

Table 4-17 presents the average CO by room for the control homes over the 2 day monitoring period. The kitchens had the largest range and greatest average.

Table 4-17: Average CO concentration by room (2 day measurement period in each home)

Rooms	CO (ppm) - Control homes, n = 5
Kitchen – average	1.1
Standard deviation	0.4
Range	0.8 - 1.7
Living room – average	0.6
Standard deviation	0.2
Range	0.3 - 0.8
Bedroom – average	0.1
Standard deviation	0.1
Range	0.0 - 0.2
Indoors – average	0.7
Standard deviation	0.5

There is no significant difference between the average of kitchens from the main study homes and the kitchens of the control homes ($t = 0.89$, $df = 18$).

4.4.2 Nitrogen dioxide

Table 4-18 presents the average NO_2 concentration measured by diffusive samplers in each room for the control homes.

Table 4-18: NO_2 concentration by room

Rooms	NO_2 (µg m^{-3}) - Control homes, n = 5
Kitchen – average	33.3
Standard deviation	23.8
Range	13.9 – 73.3
Living room – average	23.9
Standard deviation	9.7
Range	14.9 – 36.2
Bedroom – average	16.0
Standard deviation	11.5
Range	6.3 – 35.7
Indoors – average	24.4
Standard deviation	16.7

(Note: the dining room data for SA2 is classed as the living room for the controls).

The mean concentrations in the kitchens of the control homes are significantly higher than in the main study home kitchens (t = 3.19, df = 18). This is also the same for the living rooms (t = 4.04, df = 16) and the bedrooms (t = 2.13 df = 18).

4.4.3 Ultrafine particles

Table 4-19 presents the activities and the average and maximum concentrations for the control homes monitored during the heating season. Two

pilot study homes had UFPs monitored (H3 and H5), their data is included in Table 4-19 showing the maximum, average and activities that occurred during operation of the UPC in the control homes.

Table 4-19: Average and maximum levels of UFP in the control homes

House	Average UFP (pt cm^{-3})	Maximum UFP (pt cm^{-3})	Activities
SA1	47,993	500,000	Cooking (gas)
SA2	141,137	500,000	Cooking (electric), butane spray, gas fire, ironing
WV1	210,059	499,600	Cooking (gas), hairspray
CC1	24,688	43,305	Gas cooking before monitoring
H3	17,289	78,000	Cooking (gas & electric)
H5	22,335	287,000	Cooking (gas)

Table 4-20 presents the average concentration for the four control homes monitored. The average concentration is approximately double that to the average of the main study homes.

Table 4-20: Average data for UFP of the main study and control homes

Kitchen	UFP (pt cm^{-3}) - Control homes, n = 4
Average	105,969
Standard deviation	85,711
Range	24,688 – 210,059

4.4.4 VOCs

Table 4-21 presents the TVOC concentrations and activities that occurred in the homes when the PID was operated for control homes. The average TVOC level for the five main study homes was 665 µg m^{-3} and for the four control homes was 626 µg m^{-3}: there was no significant difference between the two averages (t = 0.08, df = 9).

Table 4-21: Average and maximum TVOC concentrations monitored by PID for control homes

House	Average TVOC (µg m^{-3})	Maximum TVOC (µg m^{-3})	Activities
SA1	1,453	7,722	Cooking (gas), butane spray
SA2	442	5,580	Cooking (electric), deodorant
WV2	599	5,141	None
CC1	9	860	Gas cooking before monitoring

4.5 Modelling

Two different scenarios were explored for the modelling for a two hour cooking period using the approach discussed in Section 3: a worst case scenario, where emission rates are high and ventilation low and a normal scenario, with typical emission and ventilation rates. Modelling was performed on INDAIR C++.

4.5.1 Worst Case Scenarios

Using Equation 3-2, for the cooker with high production of CO observed in SA1, the emission rate (ER) using the room volume of 26.3 m^3, a monitored maximum concentration of 66.0 mg m^{-3}, an air exchange of 0.8 h^{-1} to give 0.38 mg s^{-1} (ER – A). Using Equation 3-3, the emission rate was calculated to be 0.59 mg s^{-1} (ER – B). The differences between the estimations of the

calculations of emission rates from the two equations could include that Equation 3-3 does not account for the air exchange in the room and Equation 3-2 does not account for time of the source. The maximum emission rate of 1.42 mg s^{-1} from a flueless gas cooker with two hobs with pans on maximum heat calculated by Upton *et al.* (2004) and used in their modelling, as found in the literature review, will also be used in this modelling (ER – C).

Table 4-22 has the results for the maximum 15 minute, 1 hour, 8 hour and 24 hour time weighted averages (TWA) of the different modelled scenarios, for which the scenarios are described below, all scenarios have the room dimensions of the eco home described in Section 3.2:

Scenario 1: ER – A was used as the cooking source for the 2 hour period. An air exchange rate between the internal rooms to the outdoors of 0.1 h^{-1} was used. No internal exchange with the other rooms was used in this scenario, such as to demonstrate that the internal doors are closed.

Scenario 2: ER – A was used and an indoor - outdoor air exchange rate of 0.1 h^{-1}. No internal air exchange between the living room - bedroom and the kitchen - bedroom was applied but the kitchen - living room had an air exchange of 0.5 h^{-1}, to demonstrate that the kitchen/living room internal door is open to some extent allowing air exchange between the rooms.

Scenario 3: ER – B was used and an indoor - outdoor air exchange rate of 0.1 h^{-1}. No internal exchange with the other rooms was used in this scenario.

Scenario 4: ER – B was used and an indoor - outdoor air exchange rate of 0.1 h^{-1}. No internal air exchange between the living room - bedroom and the kitchen - bedroom was applied but the kitchen - living room had an air exchange of 0.5 h^{-1}.

Scenario 5: ER – C was used and an indoor - outdoor air exchange rate of 0.1 h^{-1}. No internal exchange with the other rooms was used in this scenario.

Scenario 6: ER – C was used and an indoor - outdoor air exchange rate of 0.1 h^{-1}. No internal air exchange between the living room - bedroom and the kitchen - bedroom was applied but the kitchen - living room had an air exchange of 0.5 h^{-1}.

Table 4-22: Modelled simulations using INDAIR C++ for high emission rate and low ventilation rate for a two hour cooking period

Scenario	Maximum 15 min TWA (CO / ppm)	Maximum 1 hour TWA (CO / ppm)	Maximum 8 hour TWA (CO / ppm)	Maximum 24 hour TWA (CO / ppm)
1	K – 31.4 L – 6.3 B – 2.3	K – 29.2 L – 6.3 B – 2.3	K – 17.0 L – 5.3 B – 1.8	K – 6.2 L – 1.9 B – 0.6
2	K – 25.5 L – 11.4 B – 3.6	K – 23.1 L – 11.3 B – 3.6	K – 12.8 L – 8.2 B – 3.1	K – 4.7 L – 3.0 B – 1.0
3	K – 48.7 L – 9.8 B – 3.6	K – 45.3 L – 9.8 B – 3.6	K – 26.4 L – 8.2 B – 2.8	K – 9.6 L – 2.9 B – 1.0
4	K – 39.6 L – 17.6 B – 5.6	K – 35.9 L – 17.5 B – 5.6	K – 19.9 L – 12.7 B – 4.7	K – 7.3 L – 4.6 B – 1.6
5	K – 117.3	K – 109.0	K – 63.5	K – 23.1

	L – 23.6 B – 8.7	L – 23.5 B – 8.7	L – 19.8 B – 6.8	L – 7.1 B – 2.3
6	K – 95.4 L – 42.4 B – 13.5	K – 86.3 L – 42.1 B – 13.5	K – 47.9 L – 30.5 B – 11.4	K – 17.5 L – 11.1 B – 3.9

K = kitchen, L = Living room, B = Bedroom

4.5.2 Normal scenarios

For this scenario, an emission rate was calculated from monitored data collected from MK1 where the cooker was less than a year old. Equation 3-3 was used to calculate the source rate, where the maximum concentration was 15.9 mg m^{-3}; the source rate was calculated to be 0.20 mg s^{-1} (ER - D). Results are presented in Table 4-23.

Scenario 7: ER – D was used and an indoor - outdoor air exchange rate of 0.5 h^{-1}. No internal exchange with the other rooms was used in this scenario.

Scenario 8: ER – D was used and an indoor - outdoor air exchange rate of 0.5 h^{-1}. An internal air exchange between the living room – bedroom, the kitchen – bedroom and the kitchen – living room was set at 0.5 h^{-1}.

Scenario 9: ER – D was used and an indoor – outdoor air exchange rate of 0.5 h^{-1}. No internal air exchange between the living room – bedroom and the kitchen - bedroom was applied but the kitchen – living room had an air exchange of 1 h^{-1}.

Scenario 10: ER – D was used and an indoor – outdoor air exchange rate of 0.1 h^{-1}. No internal exchange with the other rooms was used in this scenario.

Scenario 11: ER – B was used and an indoor – outdoor air exchange rate of 0.5 h^{-1}. No internal exchange with the other rooms was used in this scenario.

Scenario 12: ER – B was used and an indoor – outdoor air exchange rate of 0.5 h^{-1}. An internal air exchange between the living room – bedroom, the kitchen – bedroom and the kitchen – living room was set at 0.5 h^{-1}.

Scenario 13: ER – B was used and an indoor – outdoor air exchange rate of 0.5 h^{-1}. No internal air exchange between the living room – bedroom and the kitchen - bedroom was applied but the kitchen – living room had an air exchange of 1 h^{-1}.

Table 4-23: Modelled simulations on INDAIR C++ for normal / high emission rates and normal / high ventilation rates for a 2 hour cooking period.

Scenario	Maximum 15 min TWA (CO / ppm)	Maximum 1 hour TWA (CO / ppm)	Maximum 8 hour TWA (CO / ppm)	Maximum 24 hour TWA (CO / ppm)
7	K – 12.2 L – 1.5 B – 0.2	K – 11.0 L – 1.4 B – 0.2	K – 4.3 L – 0.8 B – 0.2	K – 1.4 L – 0.2 B – 0.1
8	K – 10.1 L – 3.4 B – 0.5	K – 9.1 L – 3.3 B – 0.5	K – 3.3 L – 1.5 B – 0.3	K – 1.1 L – 0.5 B – 0.1
9	K – 8.8 L – 4.5 B – 0.7	K – 7.9 L – 4.2 B – 0.6	K – 3.0 L – 1.8 B – 0.4	K – 1.0 L – 0.6 B – 0.1
10	K – 16.5	K – 15.3	K – 8.9	K – 3.3

	L – 3.3 B – 1.2	L – 3.3 B – 1.2	L – 2.8 B – 1.0	L – 1.0 B – 0.3
11	K – 35.9 L – 4.3 B – 0.7	K – 32.5 L – 4.2 B – 0.7	K – 12.6 L – 2.3 B – 0.4	K – 4.3 L – 0.8 B – 0.2
12	K – 29.8 L – 9.9 B – 1.5	K – 26.9 L – 9.1 B – 1.5	K – 10.0 L – 4.4 B – 0.9	K – 3.4 L – 1.5 B – 0.3
13	K – 25.9 L – 13.2 B – 1.9	K – 23.3 L – 12.5 B – 1.9	K – 8.8 L – 5.4 B – 1.1	K – 3.0 L – 1.8 B – 0.4

K = kitchen, L = Living room, B = Bedroom

From calculations of emissions in a controlled chamber experiment, Upton *et al.,* (2004), found average emission rate used for their modelling was 0.10 mg s^{-1} (ER – E). The concentrations for ER – E can be calculated by halving the scenarios from those calculated for ER – D (Table 4-9, scenarios 7 – 10). The modelled scenarios where the maximum TWA exceeds WHO indoor air quality guidelines for CO are shown in Table 4-24, where the room it was exceeded in is also defined. Scenarios 10 and 13 are included as exceeding 8 hour guidelines as they are 8.9 ppm and 8.8 ppm for their respective maximum 8 hour concentrations (rounded to the nearest whole number are 9ppm).

Table 4-24: Scenarios modelled in INDAIR C++ exceeding WHO indoor CO guidelines by room

Room	Scenarios exceeding 15 min WHO CO guideline	Scenarios exceeding 1 hour WHO CO guideline	Scenarios exceeding 8 hour WHO CO guideline	Scenarios exceeding 24 hour WHO CO guideline
Kitchen	5, 6	1, 3, 4, 5, 6, 11, 12	1, 2, 3, 4, 5, 6, 10, 11, 12, 13	1, 3, 4, 5, 6
Living room	-	6	4, 5, 6	5, 6
Bedroom	-	-	6	-

5 Discussion

5.1 Study design and implementation

Measurements of CO and some other combustion generated pollutants have been carried out in a sample of 14 homes, and although not rated against the code for sustainable homes, they were all built or retrofit post 2007. Initially, 20 homes were targeted, but this was found to be difficult to reach due to problems with recruitment of participants from newly built homes and the constraints of the study, such as the short time to complete measurements within the heating period and available resources. In addition, five older homes built to lower standards of energy efficiency were also monitored.

A problem encountered during the project occurred in the initial stages of recruitment. It was found that until compensation was offered to participants, there was a problem in reaching out to potential participants. As soon as this was identified, amendments were made to the study protocol regarding the recruitment process, which were addressed by the ethics committee and approved that participants could be awarded gift vouchers or a CO alarm for

their participation. First off, just CO alarms were offered, and this increased the response but not greatly. This could have been due to potential participants already having alarms installed already.

Subsequently either a CO alarm or a gift voucher was offered and this did result in a greater response. This problem of recruitment was not fully foreseen and in retrospect, participant compensation could have been offered from the start. Over 150 letters were dropped, which also on occasion included speaking to occupants of the homes to explain the study. Although cold calling door to door is more time consuming, it could be effective if the homeowners could be reached. Also there is an issue with calling during office hours when many people would be working. People that were approached this way appeared to gain an understanding of the project through it being explained in a friendly manner, as opposed to reading a ‘faceless’ letter. Although potential participants were encouraged to phone or email if interested and wanting further information to that given in the initial letter, the letter may be mistaken for “junk” mail and discarded.

The participation response could probably be greater if a higher reward incentive was offered, as the high street gift voucher was of quite low value (£20) value and the CO alarm of similar monetary value. The study protocol could now be used to recruit more homes if required more effectively then at the start of the study. The 14 participants of the main study homes, except for a couple inquiries and a couple incidences where a monitoring date couldn’t be arranged, were all that came forward to take part. As well as the direct approach to householders, over 20 housing associations and local councils were contacted to seek assistance with recruitment to the study but this was to little avail. Possibly the financial climate and possible concerns that the building evaluation could generate concern about IAQ among residents may have been factors discouraging greater involvement by housing associations and local authorities.

Appliance manufacturers and installers were approached by e-mail to request any information on sources of CO, the safeguards and the possible risks of CO

exposure arising from normal use, equipment failure and misuse. Also requested was data on emissions and any information about research and actions to minimise risks to occupants from exposure to combustion gases. Few responded, although some provided details of available literature such as the standard BS 7967 (see Appendix B). A couple identified that the majority of gas appliances are room sealed and flued externally, and should not contribute to indoor air concentrations of CO, with the main flueless gas appliance being cookers. The possibility of poor adjustment of gas valves in boilers and not following manufacturer's instructions was suggested as a possible risk due to misuse where the possibility of CO levels into the thousands of ppm could occur. Regarding research and actions, several were identified; i) work on combustion management systems to maintain combustion efficiency by automatically adjusting the gas and air ratios, ii) the introduction to domestic boilers of flue combustion monitoring and iii) research into future flue sensors to improve combustion and safety but costs could be prohibitive.

5.2 Occupant behaviour

The participants were adults, 10 of those in the 14 main study homes were women, and in the control homes two were women. The majority of the participants spent more than 70% of their time in the home, with the bedroom and living room the most common rooms where the majority of their time was spent. Kornartit *et al*., (2010) found that their 60 winter volunteers in a UK personal and microenvironment study of exposure to indoor and outdoor NO_2 spent 80% of their times indoors, with over 50% spent at home and approximately 30% of time spent at work. There was only one home where the amount of time spent in the home was less than 50% in the current study. Windows were mainly shut in the monitoring period of the homes monitored, WS1 had one bedroom window open throughout the monitoring period but generally windows were shut.

Cooker hoods were used during about one third of the cooking events in the main study and control homes. Two of the control homes did not have a cooker

hood and six of the 19 homes did not use a cooker hood once whilst cooking. One home had no cooking activities during the period when the activity diaries were filled in. Only two homes used the cooker hood on the high speed setting. Singer *et al*., (2011) in their study of capture efficiency of cooker hoods found that the lowest speed setting, which is quietest and therefore most likely to be used, was not effective in the removal of burner exhaust. A recent study where a model was used to calculate time resolved indoor concentrations of CO, NO_2 and formaldehyde produced from natural gas cooking in the home and from entry of outdoor air suggested that operation of natural gas hobs without venting via kitchen exhaust systems could lead to residential short term NO_2 that exceed air quality standards (Lobscheid *et al*., 2011). The 1 hour NO_2 guideline cannot be observed in the current study as no short term NO_2 measurements were made.

5.3 Carbon monoxide

None of the homes monitored exceeded any WHO indoor air guidelines for CO and throughout the main study monitored levels were well below the guidelines. The maximum 15 minute average was 10.5 ppm for the main study and five of the 14 homes monitored exceeded 4 ppm for a maximum 15 minute average. Milner *et al.,* (2006) in their study of London offices found that their 15 minute averages did not exceed 4 ppm, where the majority of the CO within the offices monitored was from outdoor sources. Offermann (2009) monitored 108 new Californian homes in a multi-seasonal study, observing 1 hour averages to range from 0.4 – 4.4ppm, the maximum 1 hour average in the current study was observed to be 6.3 ppm.

Raw *et al*., (2004) also found concentrations to be significantly higher in the kitchens to that of bedrooms, which was also observed in the current study, due to sources of combustion, namely cooking sources found in the kitchen. Longer monitoring periods and a larger group of homes for both groups would provide a stronger basis for comparison, as the homes monitored are not necessarily representative of the wider population, and activities over two days may not be

representative of the occupant's typical behaviour. There was also a significant difference in the average concentrations between the living room and bedroom, which occurred due to the location of the living room in relation to the kitchen, which will generally be adjacent to the kitchen, and in some cases where kitchens and living rooms were of open plan design, there was no walls or doors dividing the two rooms. In comparison to the main bedroom, which will in most cases would be separated by doors and walls, which Ferro *et al.,* (2009) found when shut are effective at preventing the transport of tracer gasses in test homes.

The three homes which have electricity as the only fuel for cooking are among the lowest for the maximum 15 minute CO average (MK5, MK9 and LB1). MK3 also has a low maximum for the 15 minute average, although gas cooking was reported multiple times, the other monitor in the kitchen with a lower resolution did report a higher 1 minute maximum (2.7 ppm compared to 1.7 ppm) than the monitor used for the average. MK3 also has the lowest maximum for the 1 hour, 8 hour and 24 hour averages and the electric cooking homes are also among the lowest observed for these maximums.

The highest short term average observed in the main study homes was from MK1, where short term peaks in the kitchen are greater than the 9 ppm 8 hour average advised by the WHO, but no guidelines were exceeded. Of all the homes monitored, none of the WHO indoor air guidelines for CO were exceeded, however one of the properties monitored as a control home, SA1, was issued a recommendation letter for servicing of the gas cooking appliance due to a highly elevated level of CO. This was produced during a cooking period of less than an hour on a gas cooker which involved the use of both the hobs and the oven where, if used for longer, levels that exceed CO guidelines are likely to occur. The occupant in SA1 was over 70 years of age, in a recent report it was observed that the risk of fatality in a CO incident is five times greater for someone 70 years or older and suggests that appliance replacement schemes should be introduced as the proportion of elderly gas users is increasing (Gas Safety Trust, 2011a).

The 1 minute concentrations for the homes ranged from 0 – 13.9 ppm for the main study homes and 0 – 58.9 ppm for the control homes. Maximums for the homes were observed from combustion within the home where applicable, mainly from gas cooking. Homes without gas cooking did not have maximums that were much different to background levels. Monitoring was performed twice in MK4 as during the first monitoring period there were problems with the mechanical ventilation in this property, the monitoring was performed a month apart and CO and NO_2 were actually slightly higher the second monitoring period with the fully functioning mechanical ventilation.

The house with the highest average for the living room and kitchen was MK8, which had a higher 1 minute maximum peak and average in the living room which was of open plan design with the kitchen. Despite having the largest average values in MK8, the 1 minute maximum for the kitchen and living room were 2.6 and 3.6 ppm observed during one of the three gas cooking events involving the gas hobs.

For the control homes the CO averages ranged from 0.8 – 1.7 ppm for the kitchens, 0.3 – 0.8 ppm in the living rooms, and 0 – 0.2 ppm for the bedrooms. An office was also monitored with an average of 0.2 ppm and a dining room with two monitors ranging from 0.2 – 0.5 ppm. Crump *et al.,* (2005) found average CO concentrations over 14 days in 37 English homes in winter to be 0.1 ppm and 0.2 ppm in the living room and the kitchen respectively. The overall average for all kitchens in the main study is 1.0 ppm, for all the living rooms is 0.9 ppm and for all the bedrooms 0.3 ppm. For the control homes the average for all homes in the kitchen is 1.0 ppm and the living room is 0.6 ppm.

In a study of 56 UK homes in the winter of 2002/2003, the average CO for all homes was found to be 1.9 ppm (Croxford *et al*., 2005). The average of all of the main study homes maximum 24 hour concentrations from is lower at 1.4 ppm and for the control homes is 1.6 ppm and average indoor concentrations were found to be 0.8 and 0.7 ppm for the main study and control homes.. Croxford *et al*., (2006) found that 50 out of 270 UK homes monitored exceeded the 8 hour WHO guideline of 9 ppm, whereas none of the homes monitored in

the current study exceeded this limit. The homes monitored in Croxford's study were low income homes and CO guidelines were exceeded due to poorly maintained and installed appliances and were mainly terrace houses, compared to the present study where the majority of homes and appliances were new. Three of the 14 main study homes were terrace, two being end terrace and one mid-terrace. Recently, a Gas Safety Trust report (2011a) observed that terrace properties have an associated high risk of CO incidents. Further work would need to be done to assess if the energy efficient home build types had an effect on CO concentrations.

Averages in the kitchen over 14 days in 830 UK homes were found to be 0.4 ppm (Raw *et al*., 2004). For the current study the average in the kitchens for the main study ranged from 0.5 – 1.5 ppm (on average 1 ppm) over the whole monitoring period (approximately two days) and for the control homes ranged from 0.8 – 1.7 ppm (on average 1.1 ppm).

Willers *et al*., (2006) found weekly average levels of 0.4 ppm in Dutch homes and Lai *et al*., (2004) found average levels of similar magnitude of 0.3 ppm in a personal exposure study in Oxford over 48 hours; the average level from the main study and control homes are about double the levels in these studies.

Fortmann *et al*., (2001) observed average CO for cooking activities to be between 1 – 5 ppm with a maximum peak of 11.4 ppm. In comparison six of the main study homes exceeded 5 ppm due to gas cooking sources with a maximum observed in MK1 of 13.9 ppm. Out of the 14 monitored main study homes, one had no reported cooking activities and three had solely electricity as the cooking fuel; these homes did not exceed 5 ppm. The electric cooking homes did not exceed 1.7 ppm in the kitchen and the home where no cooking activity occurred peaked at 3.3 ppm.

Biomass appliances were not monitored in the study and although TW1 had a biomass stove for heating in the living room it was not used during the monitoring period. It is thought that achieving code level 4 homes will require renewable fuel and energy sources, such as biomass (Gaze *et al*., 2010).

Emissions of CO and other combustion pollutants will vary depending on the type of biomass fuel and composition as well as completeness of combustion.

None of the homes monitored had tobacco smoking occurring or flueless heating appliances. Flueless heating appliances can be an indoor source of CO, Francisco *et al*., (2010) found that 20% of their sample homes with flueless heaters exceeded the WHO 8 hour average guideline of 9 ppm. Flueless gas heating appliances may be problematic in some English homes as in 2009, 18% of homes in England were classified as being in fuel poverty (homes having to spend more than 10% of income to fuel their home), which has increased every year from 2003. These homes may not be able to afford to run gas central heating and could turn to unvented gas or liquid fuel heaters as an alternative.

Appendix G presents data from monitoring other microenvironments in the present study. Multiple car journeys were monitored, where average CO ranged from 0.4 – 1.3 ppm and the maximum CO concentration was 3.2 ppm. This is similar to the range in the homes monitored in the study; the maximum of all the journeys is moderate compared to peaks that can be observed in the home, particularly those associated with gas cooking. An office was also monitored for CO, where levels were low with an average of 0.2 ppm and a maximum of only 0.4 ppm, much lower than the average in office's found by Milner *et al.,* (2006) with an average of 4 ppm.

Homes in rural areas were found to have lower levels of CO than more densely populated areas in the study reported by Raw *et al.,* (2004), suggesting an impact of outdoor sources, such as traffic, on the indoor environment. Milner *et al.,* (2006) observed CO levels to be greater in offices facing busy roads than other offices on the same floor. Fortmann *et al.,* (2001) found outdoor levels to range from 0.1 – 1.1 ppm when indoor levels during cooking activities ranged from 0.4 – 20 ppm. Offermann (2009) monitored new Californian homes and found 1 hour averages ranging from 0.4 – 4.4 ppm indoors and 0.4 – 4.9 ppm outdoors. In the present study CH1 and CH2 were the only two rural homes to be monitored, outdoor levels were not monitored for CO and these two homes

had levels indoors impacted by gas cooking. Therefore it is not possible to draw conclusions about rural versus urban homes.

It is possible that if failure of the mechanical ventilation occurred in a home with this ventilation strategy, similar to that reported by the householder in MK4 (where the air supply feature of the mechanical ventilation was not functioning in monitoring period 1), then mean levels of CO could get to levels that affect human health. In MK4, there was no evidence from the CO results that the partial failure of the mechanical ventilation had an impact on the CO levels (could perhaps be because the air extract was still in operation). The maximum 24 hour average CO was in fact higher in the monitoring period where the ventilation was believed to be fully functioning. However it was reported that the air felt cleaner in this monitoring period compared to the stale air when it was not fully functioning.

The main influence that was observed for increases in indoor CO was from gas cooking. The use of gas heating did not seem to have a great effect on the monitored CO in the homes, as during periods when it was reported that gas heating was used, there was not an obvious influence of the CO in the monitors in the vicinity of the appliance. In the control homes an old cooker was found to emit high levels of CO, this had not been serviced recently and was in the home of a group deemed to be high risk to CO poisoning – the elderly. With the increase of fuel poverty, people may not be able to afford the servicing or new appliances when needed. The high emissions found illustrates the importance of the householders, due to the role of servicing, which is not legally required but is recommended, and also with respect to the use, or lack of use, of ventilation provision such as cooker hoods. In the current study these were used in only a third of all cooking activities, the majority of which did not apply the highest and most effective, yet noisiest setting. In new energy efficient homes, where air tightness will be greater to lower thermal loss, the importance of appliance maintenance may be greater, and with the use of mechanical ventilation to control ventilation, the maintenance of these systems will also be essential in ensuring levels of indoor air pollutants do not impact human health.

5.4 Nitrogen dioxide

There is a larger average difference between the bedroom and the kitchen than the kitchen and the living room, suggesting that there is movement of air from the room with the combustion source to the living room, and the bedroom is less impacted by this transfer. Raw *et al*., (2004) found that levels were significantly higher in kitchens than in bedrooms, accounted by the cooking related sources of NO_2 in the kitchen, where the indoor concentrations were most greatly impacted by the cooking fuel. This was also observed in the current study, with bedrooms being significantly lower in concentration than kitchens.

Out of the 14 homes, three had the maximum concentrations of NO_2 observed in rooms other than the kitchen which were MK6 (living room), MK8 (living room and bedroom) and TW1 (bedroom). Averages for the kitchen are 2.5 times greater in the control homes than the main study and the living room and bedroom concentrations in the control homes are approximately double that of the main study homes. The control home kitchens were significantly higher than the main study home kitchens, this suggests that the appliance age and state plays a big part in the accumulation of indoor air pollution, and as newer air tight homes are developed, annual servicing of combustion appliances may be more critical.

All NO_2 concentrations in the main study homes were well below the recommended WHO annual guideline of 40 µg m^{-3}, the highest observed being 23.7 µg m^{-3} in the kitchen of WS1 and the bedroom of TW1. Three out of the five control homes had concentrations higher in their kitchens than the maximum observed for the main study homes and one of the three (WV2) exceeded the annual guideline in the kitchen with a value of 73.3 µg m^{-3}, although this was monitored over 0.07 years and the guideline is not to be exceeded over a year. The three control homes with the higher NO_2 were all solely fuelled by gas for cooking and heating.

MK9, which had gas and electric cooking and gas central heating, had the lowest NO_2 levels monitored in the main study, where the maximum NO_2

observed in MK9 was 3.4 µg m^{-3} in the kitchen. The highest concentration in the main study homes was in TW1, the only retrofit home to be monitored. Concentrations ranged from 21.3 µg m^{-3} in the living room to 23.7 µg m^{-3} in the bedroom, where the gas boiler was located. The other two homes with just electricity for cooking, MK5 and LB1, had levels similar to the averages for the main study homes where the average for MK5 in the kitchen was 12.0 µg m^{-3} and LB1 12.3 µg m^{-3}. MK7 and MK8 had small CO peaks during the two days of monitoring when the activity diaries were filled out, and had low NO_2 over the exposure period of the diffusive tubes used.

The NO_2 levels observed in the kitchen are comparable to that monitored by Kornartit *et al.,* (2010), where Palmes tubes were used to monitor 60 UK homes, and concentrations ranged from 15.3 µg m^{-3} in a kitchen with electric cooking appliances to 74.3 µg m^{-3} in a kitchen with a gas appliance. McKay *et al*., (2010) found that the average concentration for the 22 monitored homes built in compliance with 2006 Building Regulations was 24 µg m^{-3}, which is more than double the 10.6 µg m^{-3} found in the current study. Four of the 22 homes also exceeded 40 µg m^{-3} whereas none of the new and retrofit homes in the current study were close to this level. Two of the kitchens monitored did exceed 40 µg m^{-3}, these being one in a control home and one in a student hall of residence (Appendix G).

Raw *et al.,* (2004) found two week averages in the kitchen to be 21.8 µg m^{-3} in 845 English homes, with a maximum of 620 µg m^{-3}. This average is approximately 60% greater than the average found in the kitchens in the current study, but lower than the average of the control homes kitchens. The maximum in the current study for all homes did not exceed 73.3 µg m^{-3}. Raw *et al.,* also found that smoking had a significant impact on the NO_2 levels in the bedroom and was significantly impacted in kitchens by type of area, dwelling type, age of home, season and by unvented heaters.

Appendix G shows additional NO_2 measurements. Two cars were monitored by the participant from SA2 and a resident of the student halls, and both levels were found to be less than 20 µg m^{-3}. The SA2 car was used more frequently

but was lower in concentration than the car from the halls. The bedroom and kitchen of the halls were also monitored for two weeks and the kitchen was found to exceed the 40 µg m^{-3} annual limit. The kitchen had no gas cooking source but a gas central heating boiler was located there, which was constantly on. The car was parked outside this kitchen which may explain the higher level found in this car, as the area was rural with low traffic and therefore would probably not have a great impact on these levels. As discussed for CO, an office which was monitored had low CO levels and this also had a fairly low average NO_2 over a couple of weeks with a value of 10 µg m^{-3}.

The front garden of the control home WV1, which is adjacent to a busy road, and the back garden, which has three neighbouring homes, were monitored and were found to have 27.6 µg m^{-3} and 27.3 µg m^{-3} respectively. The kitchen was found to have a higher average level than the gardens, but the gardens were more than two times higher than in the bedroom and almost two times higher than in the living room. Raw *et al.,* (2004) found levels in the bedroom to be lower in each season but were closest to outdoor levels in summer, when it is more likely windows would be opened. Levels indoors are impacted by air exchange between rooms, building type and furnishings to which NO_2 can reactively decay on the surfaces, as well as indoor sources. In the absence of an indoor source, indoor NO_2 will be lower than outdoor levels because of losses by chemical reaction in air and at surfaces (WHO, Regional Office for Europe, 2010).

5.5 Particles

The average concentration measured in all main study homes is approximately half that in the control homes and the home with the highest average concentration is a control home with an approximately 90,000 pt cm^{-3} higher value than any main study home. MK1 had a maximum level that was low in comparison to the other homes, but it is noted that no combustion or cooking activity occurred during the monitoring period. The duration of operation varied due to battery life and although there is a potential for continuous operation for

8 hours before the alcohol wick must be replenished, this length of time was not always achievable.

MK2 had gas cooking activities just before the monitoring process, and the 500,000 pt cm^{-3} maximum was achieved in the first minute of the monitoring and steadily decreased over the monitoring period. During this time the CO was not highly elevated but started off around 1 ppm and fell to 0.5 ppm when the UFP concentration in MK2 reached less than 10,000 pt cm^{-3} a few hours later. The UFP concentration then decreased further to less than 5,000 pt cm^{-3} another couple hours later before the UPC ceased operation. MK6 had a peak of UFP of around 195,000 pt cm^{-3} at the start of monitoring due to gas cooking before the monitoring had started, but the maximum of 451,765 pt cm^{-3} occurred a couple hours later, but no activities were reported in the activity diary for the kitchen or elsewhere in the home. The CO levels during this time were approximately 1.4 ppm at the start of the monitoring and 1.8 ppm when the UFP levels reached the maximum in this home.

Further evidence for an effect of gas cooking on the increase in levels of UFPs was shown in MK8, CH1, CH2 and TW1 where peaks in UFPs were observed. UFPs in MK8 reached a maximum during gas cooking, the CO also increased from a level prior to the cooking of around 1.5 ppm to a maximum of 2.5 ppm in this cooking period. CH1 had a gas cooking activity occurring during the operation of the UPC, which coincides with the maximum UFP and correlates with the maximum CO observed in CH1. Gas cooking led to the maximum UFP level observed in CH2 where the CO also correlated with an increase from the background level to the maximum observed of 8.5 ppm. TW1 had the maximum observed at the start of the monitoring period, the levels of UFP then drop over an hour to around 5,000 pt cm^{-3} and then peak at 16,751 pt cm^{-3} during a gas cooking period, with no notable change in CO during the 20 minute cooking period.

Electric cooking was also observed to be a source of UFPs in some of the homes, including LB1 where the maximum UFP count occurred during a 15 minute cooking period with the electric oven during which a candle was also lit

and extinguished 3 hours later. This appeared to be an additional source of UFPs as levels are elevated for this period. At about the time when the candle is extinguished, the UFP drops steeply over 5 minutes from over 40,000 pt cm^{-3} to 25,000 pt cm^{-3} and over the next few hours the level decreases to around 6,000 pt cm^{-3} before the monitor powered off. The CO levels were also elevated compared to the background level in the periods where the candle was lit, with a maximum of 1.7 ppm when the UFP levels were around 50,000 pt cm^{-3} and dropping to 0.8 ppm a few hours later when the UFP was below 10,000 pt cm^{-3}.

Two main study and two control homes had periods when the maximum of the monitor (500,000 pt cm^{-3}) was reached. The actual reading was probably higher than this and therefore the maximum and average given for these homes may actually be higher. The 500,000 pt cm^{-3} maximum was reached in periods of gas cooking for two of the monitors and electric cooking with the other two, and one of these (SA2) also reached the maximum when a gas fire was used. The UPC in SA2 was operated in the living room as well as the kitchen to observe other activities (ironing, gas stove and propellants).

SA1 had the highest CO observed and the maximum UFP coincides with the maximum CO levels. In SA2 where the gas fire is used and the UFP levels increases rapidly, this does not correspond to a peak in the CO. In WV1, the peak in UFP correlated to a maximum CO peak of 11.3 ppm.

CC1 had elevated UFP at the start of the monitoring due to gas cooking prior to the monitoring, the CO was also slightly elevated at approximately 2 ppm and then it declined over an hour to 1 ppm and the UFP had reached approximately 13,000 pt cm^{-3}. The UFP maximum in H3 coincides with the use of the electric oven. The use of a hob fuelled by bottled gas did not appear to impact the levels observed of UFP or CO. In H5 the maximum UFP concentration coincided with the maximums of CO, which occurred after a gas cooking period.

Cooking activities, including both gas and electric, can impact the UFP levels with concentrations observed 100 times greater during these activities compared to when no activity has occurred. Wallace *et al*., (2008) also

observed that background levels of around 1,000 pt cm^{-3} can increase to concentrations 100 times greater with cooking activities in as little of 4 minutes. Dennekamp *et al*., (2001) found frying bacon on a gas cooker produced UFP peak concentrations of 590,000 pt cm^{-3}, compared to 159,000 pt cm^{-3} when bacon was fried on an electric hob. It is not clear how levels would be different when the same cooking activities are performed on gas / electric cookers in this study, but it can be observed that both gas and electric cooking can greatly impact the UFP, as levels of 500,000 pt cm^{-3} are observed when solely gas cooking and solely electric cooking has occurred. Wallace and Ott (2011) found similarly to the current study that combustion and heating elements were found to increase the number of UFP with the highest peak concentration of 432,000 pt cm^{-3} observed from gas cooking. UFP levels nearly reached 900,000 pt cm^{-3} when frying on a gas cooker (Sjaastad *et al*., 2010). This could have been the case in the present study in some of the homes where the maximum of the UPC was reached, such as MK7 where values exceeded 500,000 pt cm^{-3} for around 20 minutes.

Wallace (2006) found the average UFP concentration with no internal source to be 2,500 pt cm^{-3} and minimum levels of UFP that occurred during times not affected by a source ranged from 1,500 – 5,485 pt cm^{-3}. The average level in MK1 where no cooking activity occurred throughout the duration of the UPCs operatation was 5,008 pt cm^{-3}, approximately double that observed by Wallace.

The total airborne particulate mass per volume concentration was monitored on a few occasions with a method most accurate for particles in the size range of 0 - 10 µm. This method is more dependent on particle size than a particle counting monitor as larger particles will contribute more to the total mass than smaller particles such as UFP as, due to their size UFP, have a low mass which is insignificant in comparison to their larger particle counterparts (Morawska *et al*., 2004).

In SA2, the maximum total particle concentration of 20,240 µg m^{-3} was observed during a 10 second burst of a butane/propane propellant deodorant spray, after which the levels soon dropped to less than 3,000 µg m^{-3} (1 minute

average). A peak of 7,290 µg m^{-3} was observed with a 10 second spray of a butane propellant hairspray. The UFP seemed to increase with the deodorant use but was not affected by the hairspray, suggesting that predominantly larger particles are produced from the hairspray.

Unlike the UPC, the total particle concentration did not seem to be affected by the use of the gas fire heater in SA2. During a cooking period when the hobs and oven were used, unlike UFP, the total particles only increased above the average level of 217 µg m^{-3} when it was reported that frying of mushrooms and steak was performed and levels peaked at 4,870 µg m^{-3} and stayed above 1,000 µg m^{-3} for over half an hour. Sjaastad and Svendsen (2008) found the maximum particle concentration when frying beefsteak using margarine was 11,600 µg m^{-3}. Average levels of total particles in SA2 were observed to be 540 µg m^{-3}. In WV1 the UPCs maximum reading occurred during the operation of a gas grill, which did not seem to affect the total particle mass concentration. The maximum total particle concentration was 1,410 µg m^{-3} and this occurred from the use of hairspray.

Wallace and Ott (2011) found UFP concentrations in vehicles to be on average around 30,000 pt cm^{-3}. In Appendix G the average UFP for a car journey on a winter evening for the participant from WV1 was 31,382 pt cm^{-3}. The average of WV1 is similar to some of the study homes with averages of about the 40,000 pt cm^{-3} although the maximum peaks in these homes are much higher compared to the maximum of 101,673 pt cm^{-3} for WV1. Maximums in the home reached 500,000 pt cm^{-3}, the maximum recordable by the UPC. The average total particle concentration for the WV1 journey was 120 µg m^{-3}. In WV1, UFP and total particles were monitored in the bedroom during the burning of an incense stick, average UFP was 46,132 pt cm^{-3}, peaking at 114,183 pt cm^{-3} and the average total particle concentration was the same as the car journey for WV1 (120 µg m^{-3}). The UFP levels were higher during the incense burning both on average and at their peak compared to the car journey for WV1 but not as high as some cooking periods monitored.

Table G-9 in Appendix G shows data over a 4 hour period in the bedroom of student accommodation where a 10 second spray of a butane propellant air spray was used and left in a room where all windows and doors were shut. The UFP count was found to increase and a maximum of 62,722 pt cm^{-3} was observed with an average of 11,735 pt cm^{-3} over the 4 hours. As expected the total particle count was greatly affected and on average was 560 µg m^{-3}, peaking at 3,780 µg m^{-3} shortly after the start of the spray. The UFP concentration also peaked just after the start of the spray, but the total VOC level took some time to peak, perhaps due to the delay in volatilisation of organics from the aerosol.

Currently, there are no guidelines for UFP concentrations in air but there is increasing concern that this particle fraction has greater impact on health than larger particles, with the ability to penetrate deeper into the respiratory system. $PM_{2.5}$ and PM_{10} were not monitored specifically in the current study so the PM cannot be assessed against these guidelines. A filter system to enable the total particles monitor to measure $PM_{2.5}$ or PM_{10} can be purchased from the manufacturer but was not available for the project.

PM generated from combustion of wood was found to be more toxic and induce formation of reactive radical species leading to DNA damage compared to PM in ambient air and in conditions of high oxygen during combustion predominantly UFP and fine particles were generated with higher PAH concentrations than in low oxygen combustion (Danielsen *et al*., 2011). PAHs were not specifically investigated in the current study, but can be generated from combustion and cooking. Sjaastad *et al*., (2010) observed higher levels of PAHs when frying with gas stoves compared to electric stoves, and PAHs are considered by the WHO as genotoxic carcinogens (WHO, Regional Office for Europe, 2010). Although the PID may react to the most volatile PAHs, such as naphthalene, a more specialist method, such as collection on filters and subsequent extraction and analysis by chromatography and mass spectrometry, would be required as only a minor fraction of PAH exist as volatiles (WHO, Regional Office for Europe, 1987).

5.6 Volatile organic compounds

Two different types of monitoring methods were used to determine VOC concentrations, as explained in Section 3.1. The response of the PID depends on the composition of mixtures because of the differences in detector response produced by individual organic compounds. Although not used alongside the Tenax tubes in the present study, it would be expected that there would not be a strong agreement between the two methods. The range of compounds monitored by the two methods also differs, for example the PID will detect more very volatile compounds (VVOCs) than the Tenax method.

The PIDs range of response with respect to the calibration gas, isobutylene, is 1 ppb – 10,000 ppm, which expressed as a toluene equivalent is 2 - 18,888,700 µg m^{-3}. Literature from a PID manufacturer recommends levels for total VOCs in normal indoor environments should range from 200 – 1,300 µg m^{-3} (toluene units) and should not exceed 1,900 µg m^{-3}, as levels higher than this could indicate potential IAQ contaminants (RAE Systems Inc., 1999).

The average of one home, MK9, exceeds 1,900 µg m^{-3}; no recorded activities occurred during the 2 hour period of monitoring although electric cooking had occurred prior to the monitors being set out. Three of the main study homes had maximum values that exceeded 1,900 µg m^{-3}, MK7 and MK9 had electric cooking activities, but in MK7 the electric cooking did not impact levels greatly and the maximum occurred a couple hours before the cooking with no reported activity being recorded. MK9 had cooking activities occurring prior to the monitoring and the TVOC levels were decreasing during the operation of the PID. MK8 had a gas cooking period during which the average over the 40 minute period was double that of the average for the whole period monitored, but the maximum reading occurred prior to the cooking activity when no reported activity had occurred. Gas cooking occurred prior to monitoring in MK6 and levels were raised from the average in this home and the maximum was observed towards the start of monitoring. The PID often records zero readings

for VOC for the minutely averaged data, and in WS1 the PID did not monitor any reading over the half hour gas cooking period.

SA1 and SA2 had maximums associated with use of butane sprays. In SA1 during the gas cooking period which was found to produce high levels of UFPs as well as CO, a peak of 4,360 µg m^{-3} and an average of around 1,800 µg m^{-3} was found. CC1 had a low average TVOC concentration in comparison to the other control homes and the other main study homes except WS1. CC1 had the maximum at the start of the monitoring period prior to which gas cooking had occurred, and levels decreased after half an hour and were generally not above the detection limit for the remainder of the PID's operation. There was not a consistent link established between cooking and the PID TVOC readings, as in some instances the levels would increase and on other occasions it would not have an impact. The type of cooking activity itself (such as frying or boiling), maybe the cause of the increase in TVOCs in some readings, but this information is not available to discuss as to keep the diary simple and minimal to ensure it was filled in, this detailed information was not required to be recorded by the participant. This may also explain why there was no significant difference between the main study homes PID VOC concentrations and the control homes.

Compared to the 300 µg m^{-3} 8 hour guideline value established by Communities and Local Government for TVOCs to demonstrate compliance with the AD F requirements, only two of the five main study homes and one of the four control homes monitored were below this level. These homes are WS1, MK7 and CC1. This average is to be over 8 hours and MK6, MK8, WS1, SA1 and SA2 (7.5 hours) were over this period, but shorter monitoring periods were used in MK7 (4 hours), MK9 (2hours), WV2 (3 hours) and CC1 (6 hours), so a direct comparison with an 8 hour average cannot be undertaken. WS1 is the only home to be monitored over 8 hours to be below the 300 µg m^{-3} performance value.

In CH2 and TW1, diffusive Tenax tubes were used and in both homes the bedrooms have the highest observed levels. All rooms in CH2 had levels below

300 µg m^{-3}, whereas TW1 had all levels more than double the guideline value of 300 µg m^{-3}.

The TVOC value represents a summation of many individual compounds that can be identified and quantified by the TD-GC-MS method. Decamethylcyclopentasiloxane (DMCPS) was the only significant VOC compound identified in both homes as major components of the TVOC and this compound can be found in cosmetic products and some spray treatments for textiles. TW1 was a retrofit home and was still undergoing work at the time of monitoring but was occupied as normal. It had recently had mechanical ventilation installed and future work was planned such as the installation of solar panels. The recent and on-going work may have been the reason for the increased levels of VOCs observed, where possibly inappropriate materials were used in this low ventilation retrofit home. Limonene (observed in CH2) and α- pinene (observed in TW1) concentrations can be elevated in homes with new furniture and texanol (2,2,4-trimethyl-1, 3- pentanediol monoisobutyrate), which can be found in use as a coalescing solvent in paints, was also found to be high in concentration in TW1. The level of toluene observed in TW1 was well below that of the 1 week WHO guideline.

Héroux *et al.,* (2008) found recent renovation and combustion sources contributed to a rise in some VOCs and newer homes generally had higher levels. In TW1 the gas boiler was located in the bedroom and the NO_2 levels were slightly higher in the bedroom compared to the other rooms. The TVOC level in the bedroom of TW1 was approximately double that in the kitchen, toluene was also double that found in the living room and kitchen. Héroux *et al.,* found higher concentrations of toluene for homes with gas and oil as the fuel for the main type of heating. The majority of gas appliances will be room-sealed and flued to exhaust products of combustion externally and safely to outside air and should not contribute to indoor air concentrations other than by inadvertent readmission of outside air flue products into a room or a malfunction of the flue itself. Gas cookers are the main flueless category of appliances which will give rise to emissions of CO and other indoor air pollutants related to combustion.

McKay *et al.,* (2010) reported that for a sample of homes built in compliance with 2006 Building Regulations over half had TVOC levels that exceeded the exposure guideline of 300 µg m^{-3}; two of the 22 were in excess of 600 µg m^{-3} over the one week of monitoring. In the present study one of five main study homes exceeded 600 µg m^{-3} and one of four control homes when the PID was used for monitoring TVOC levels with a maximum of 8 hours monitoring. Also one of two homes exceeded the guideline when Tenax Tubes were used to give a two week average concentration.

The Building Regulations AD F does not define how TVOC values should be measured, although it does refer to a reference indicating a GC/MS approach. An international standard, ISO 16000-6 as described previously in the literature review, defines a method of TVOC sampling using Tenax TA sorbent tubes actively via use of a pump and with determination by TD-GC-MS. This method may be best suited for TVOC determination over 8 hours but the PID is more practical as it is simpler, provides real time data and is cheaper. It is not clear how the two methods would perform alongside one another especially given the wide range of compounds that may be present in different indoor environments; further work would be needed to better understand this relationship.

Appendix G has measured data for the most significant VOCs monitored actively before and during a gas cooking period. Both TVOC values calculated were below 300 µg m^{-3}, and increased during cooking. The most notable changes are the increase of limonene and a compound of molecular formula $C_{18}H_{12}O_2$ during cooking and a decrease in DMCPS.

5.7 Modelling

The kitchen dimensions used were chosen to represent a small kitchen, equivalent to that in an ‘eco-home’ from the same estate as some of the homes monitored. The actual air volume can be even smaller than the room volume as various objects, including appliances and furniture in the kitchen will alter the volume available for dilution and gas exchange. For simplicity, the ventilation rates were kept constant throughout the scenarios, whereas in reality they may

increase or decrease due to internal and external conditions. The model did not account for the use of cooker hoods which may further lower the concentrations observed. The user of the model could possibly increase the air exchange of the room to the outdoors to simulate this, but doing so may not reflect the potential efficient local removal of fumes close to the source. It is also not mandatory to use cooker hoods or house ventilation, and as discussed earlier it was found that over half of cooking activities observed in this study did not use cooker hoods.

Approaches were made to appliance manufacturers, industry organisations, consultants on energy management and low carbon, government agencies, councils and regulatory bodies requesting information on rates of emission of CO and other gases from combustion appliances but unfortunately no useful data was forthcoming. CO emission rates used were calculated from monitored concentrations in the present study and some were taken from calculated source rates in the literature.

For scenarios using emission rate ER – E (0.10 mg s^{-1}), data was not presented as the concentrations calculated by the model would be half of that for ER – D (0.20 mg s^{-1}). These concentrations would therefore be well within the limits of WHO indoor air guidelines as scenarios 7 – 10 using ER – D does not exceed the limits, except scenario 10 is borderline on the 8 hour guideline. ER – D was approximated from a cooking activity in MK1 whereas ER – E was taken from Upton *et al.,* (2004) and related to a flueless cabinet heater on low heat position in a controlled chamber experiment.

It should be noted that in real world scenarios the level of CO in the outdoor air entering the building will be additional to that generated indoors that is the subject of this modelling exercise.

The only scenarios to exceed the 15 minute WHO guideline of 87 ppm involved ER – C, which was calculated for a flueless gas cooker with two hobs with pans on maximum heat by Upton *et al.,* (2004). The most common guideline to be exceeded was the 8 hour guideline (9 ppm). This guideline was the only one

exceeded in the bedroom, this occurred in scenario 6, although there was no direct air transfer applied between the bedroom and the kitchen or the bedroom and the living room, but 0.5 h^{-1} between the kitchen and the living room. In scenario 5 when no transfer is applied between the kitchen and the living room, the 8 hour maximum in the bedroom does not exceed the guideline.

In scenarios where no direct air exchange between rooms was applied there is still an influence of CO generated in the kitchen on the living room and bedroom. The formula used in the model for calculating the air exchange between rooms is an approximation of simultaneous air exchanges between rooms. This movement observed between rooms even with internal doors shut is expected in real buildings because walls and doors are not airtight, and higher concentrations will be observed in rooms closer to the room with the source. Ferro *et al.,* (2009) looked at the effects of door opening / closure on transport of CO and another tracer gas in test homes. They found that with doors shut airflow will still occur between rooms but closure can be an effective way to prevent the transport of air pollution between rooms, and opening of an internal door by just a few cm can increase air flow between rooms 8-fold.

In scenarios 3, 4, 11, 12 and 13 ER – B was used which was calculated from a cooking activity in SA1. Scenario 13, had the highest ventilation and was borderline on the 8 hour WHO guideline. The modelling suggests a high emission rate from an old, un-serviced or possibly faulty appliance could produce levels of CO that are harmful to human health. Increasing the ventilation in scenarios 11 and 12 compared to that in scenarios 3 and 4 resulted in the 24 hours modelled concentrations not exceeding the guideline. Scenario 4 that had a transfer between the kitchen and living room of 0.5 h^{-1} gave a 8 hour maximum modelled concentration in the living room that exceeded the 8 hour WHO guideline. Living room 1, 8 and 24 hour average guidelines were all exceeded with scenario 6.

Bone *et al.,* (2010) expressed concerns of failure of mechanical ventilation systems. For the default ventilation options in AD F 2010, zero air permeability equating to no infiltration is assumed for certain ventilation systems (continuous

mechanical extract and continuous mechanical supply and extract with heat recovery whole house ventilation systems) and 0.05 ach (passive stack ventilation and background ventilators and intermittent extract fans). If mechanical ventilation were to fail, it could be similar to the ventilation rates used in scenarios 1 – 6 and scenario 10, where 0.1 h^{-1} for each room was applied; even if mechanical ventilation were to fail some air change would be likely due to pressure differences and external conditions. In each of these scenarios, at least one WHO guideline was exceeded.

Scenarios 1 and 2 had the same ER applied; 1, 8 and 24 hour guidelines were exceeded in scenario 1 and only the 8 hour was exceeded in scenario 2. Scenario 1 had an air change rate in the kitchen of 0.1 h^{-1} while scenario 2 had 0.6 h^{-1}. Studies of American and Canadian homes by Wallace *et al*., (2008) and Héroux *et al.,* (2008) respectively, observed air change rates to range from 0.1 – 0.6 h^{-1}. Crump *et al.,* (2005) observed in their study using English homes ventilation rates ranged from 0.2 – 0.7 h^{-1} with a mean of 0.4 h^{-1} in the winter and 0.2 – 1.1 h^{-1} with a mean of 0.6 h^{-1} in the summer. The lack of use of trickle ventilators was believed to be the cause of low ventilation rates in their study. Out of the 14 main study homes, five had reported all windows had trickle vents, two had some windows with trickle ventilators and the remaining seven reported no trickle ventilators in the home. Only three of the seven homes with trickle ventilators reported the use of trickle ventilators, but it is unsure if the other homes did or did not use theirs.

In scenario 3, a similar 15 minute maximum is observed to that in SA1, although a lower air exchange is used in a smaller room in the modelled simulation compared to the kitchen of SA1, suggesting that the emission rate observed in SA1 is in fact higher.

Scenario 10 used ER – D, which was calculated from a cooking activity in MK1. The 8 hour guideline was reached in this scenario demonstrating how a moderately low emission rate coupled with low ventilation could be a risk to the health of occupants. Although not all loss of pollutants from the indoors is by air exchange, as for example for particles and NO_2 where reactions and sinks can

decrease their concentrations, in the case of CO which is relatively unreactive, air exchange is the predominant mechanism.

From the activity diaries of the participants in the current study, the majority spent more than 70% of their time in the home, with 7 out of 20 spending more than 90% of their time in the home. Most time was spent in living rooms and bedrooms with some of the homes having the kitchen as the second most inhabited room. With regards to opening of windows in the home, for 9 out of the 20 the windows were shut throughout the 2 day monitoring period. The modelling has not accounted for people's behaviour around the home, but the combination of people spending most of their time indoors in an airtight structure with no window opening and undertaking cooking without use of cooker hoods suggests a potential for exposure to elevated levels of indoor pollutants. The modelling highlighted in particular the possibility of a high emitting source of CO in the kitchen, such as an old un-serviced cooker, especially combined with low ventilation rates from indoor – outdoor, could lead to WHO indoor air guidelines being exceeded not only in the room of the source but also in other rooms of the house.

6 Conclusion

The primary aim of this project was to assess the risk to health due to CO and other combustion products released in energy efficient homes. This assessment was informed by measurement of CO and some other pollutants in some new homes and older (control) homes and by modelling the impact of source emissions on CO concentrations.

From the main findings of the study the following conclusions are drawn:

- A protocol was developed and successfully applied in homes during the field study. The main difficulty encountered in the project was in recruiting participants to the study, which was improved by the offer of incentives. The financial climate and possible concerns that the building evaluation could generate concern about IAQ among residents may have been factors discouraging greater involvement by housing associations and local authorities.

- Of all the homes monitored, no WHO indoor air guidelines for CO were exceeded. One control home however was issued a recommendation letter for servicing of the gas cooking appliance due to a highly elevated level of CO, which with extended use could exceed WHO guidelines. The sole occupant was in a group at higher risk, the elderly.

- Gas cooking had the greatest effect on CO and generally CO maximums could be linked to combustion appliances within the home.

- For the main study homes there was no significant difference in concentration between the kitchen and the living room but there was a significant difference between the kitchen and the bedroom and also between the living room and the bedroom. There was no significant difference between the average of kitchens from the main study homes and the kitchens of the control homes. Failure of the mechanical ventilation supply occurred in one of the monitored homes (with the

extract feature still functioning), but this did not lead to high levels of combustion pollutants observed in this property. This could have been more serious if the extract feature of the mechanical ventilation also failed, leading to a possible build-up of indoor air pollutants, such as CO which is relatively unreactive and removed by air exchange, leading to levels which may affect human health. Trickle ventilators were reported to be all open in this home and different occupant behaviour, such as activities and styles of cooking might have produced increased levels and thereby posed more of a problem.

- All NO_2 concentrations in the main study homes were well below the recommended WHO annual guideline of 40 µg m^{-3}. It was found that there was a significant difference between the kitchen and the bedroom of the main study homes. One of the five control home kitchens exceeded the annual guideline with a value of 73.3 µg m^{-3}, although this was monitored over 0.07 years and the guideline is not to be exceeded over a year. NO_2 concentrations were all significantly higher in the bedroom, living room and kitchen in the control homes compared to the main study homes.

- Currently, there are no guidelines for UFP concentrations in air and there is a limited literature reporting their measurement. Combustion, heating elements and some aerosols were found to increase the number of UFPs. Cooking activities, both gas and electric, can impact the UFP levels with concentrations observed to be 100 times greater during these activities compared to when no activity has occurred.

- Some cooking activities were found to impact TVOC levels measured by the photoionisation detector (PID). A consistent link was not established between cooking and the PID TVOC readings, the type of cooking activity itself may have caused the increases in TVOC observed in some of the properties. The dominant source was probably building materials and other products such as cosmetics, rather than cooking, as in two

homes where the kitchen, living room and bedroom were monitored, the bedroom had the highest levels of VOCs. In the two homes where Tenax tubes were used for measurement, bedrooms had higher levels of VOCs than kitchens and living rooms. Compared to the 8 hour 300 µg m^{-3} TVOC performance criteria showing compliance with the Building Regulations, only three of the seven main study homes and one of the four control homes were below this level.

- There is no evidence from measurements in the current study that energy efficient homes pose a greater risk to health from combustion pollutants than other homes. This is not considered conclusive as only a small number of homes were monitored and the sample did not include homes rated highly against the Code for Sustainable Homes. These may pose new risks with greater standards of energy efficiency and airtightness and the possible increased use of new biomass combustion appliances.

- Modelling performed on INDAIR C++ demonstrated how situations of low ventilation (such as may occur if the mechanical ventilation system fails in a home using this ventilation strategy) combined with high source emission rates can lead to air quality guidelines being exceeded. High source emission may well result from old and poorly maintained cookers and the current trend of increased fuel poverty may lead to a higher incidence of such sources. Also, a moderately low emission rate can exceed air quality guidelines if adequate ventilation is not provided; this applies particularly to the most commonly exceeded guideline in the modelling which was the 8 hour guideline of 9 ppm. For CO, ventilation is particularly important because it is a relatively unreactive gas and therefore only removed through ventilation rather than by reaction with surfaces or other substances in the air.

- If not ventilated externally, rooms other than that containing the source can also have elevated CO concentrations and exceed air quality

guidelines. As was shown by the participants completing the activity diary, windows were kept shut, cooker hoods were generally not used and most participants spend 70% of their time in the home. Using modelling, the combination of people spending most of their time indoors in an airtight structure with no window opening and undertaking cooking without use of cooker hoods suggests a potential for exposure to elevated levels of indoor pollutants. For further insight, better input data would be required, as there was a lack of data on emission rates in literature and they were also unable to be provided from industry. There was similarly limited information on ventilation rates in energy efficient homes and the transfer rates of air between rooms.

- The sample of homes used in the study cannot be considered to be representative of the UK as a whole, a large proportion were from one area of England and they were mainly located in suburban or urban areas. Also the two day main monitoring period may also not be representative of an occupant's typical week, and different occupant behaviours may influence levels of pollutants and the amount of exposure of occupants in homes.

There is a general lack of knowledge and data on indoor air quality in energy efficient homes and this study can only be considered as a preliminary investigation, but it provides valuable indicative data and a basis for recommendations for required further work.

7 Recommendations for further work

- Longer monitoring periods and a larger group of homes (energy efficient and controls) would provide a stronger basis for assessment, as the homes monitored are not necessarily representative of the wider population and activities over two days may not be representative of the occupant's typical behaviour. Also this could clarify the impact of particular parameters such as the use or misuse of trickle ventilators and mechanical ventilation systems. Parallel outdoor concentrations could be measured to see how combustion pollutants from outdoor air impacts indoor levels.

- Explorations of house build type as well as location (area type) to assess their impact on CO and other combustion product concentrations in energy efficient homes.

- Monitoring of highly rated Code homes, with greater standards of energy efficiency than the homes monitored in the current study. Homes with biomass appliances need to be explored further, as well as the effects of tobacco smoking or flueless heating appliances as none were monitored currently. This should be more feasible than when this study was initiated as a number of housing developments of this type have now been completed.

- More in depth modelling to explore multiple sources, impact of outside sources, multiple pollutants, such as NO_2 and PM, and exploration of ventilation, such as cooker hoods, as ventilation rate was kept constant throughout the modelled scenarios.

- Regarding the methods used to monitor VOCs, comparison of the two methods (PID and sorbent tube) to see how concentrations correlate. Also further application of these monitoring methods as the current study and previous studies indicate a possibility that the performance criteria for TVOC in air may be quite commonly exceeded in new homes.

- Additional measurements of other important combustion pollutants, such as formaldehyde, PAHs and $PM_{2.5}$. Also short term measurements of NO_2 to assess against 1 hour guidelines.

- Simultaneous measurements of ventilation to assess air exchange rates which could also be applied in modelling.

- Personal exposure monitoring, with monitors attached to occupants, could also be undertaken coinciding with the stationary monitoring to assess the actual exposure that occupants encounter, which may be different from that inferred from fixed site monitors.

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APPENDICES

Appendix A Literature searches

Online database searches have been undertaken on combustion products, indoor air quality, health effects of combustion products and energy efficient homes. The following strategies have been used to access particular published scientific papers and journals for inclusion in the review. Focus was on homes primarily from the UK and other western developed countries.

For health effects of the indoor combustion products under consideration (carbon monoxide, nitrogen dioxide, sulphur dioxide and VOCs), reviews and guidelines were reviewed.

For recent up to date literature on energy efficient homes, biomass and standard methods for measuring air pollutants, government and standards websites were searched, such as British Standards and Communities and Local Government. As standards and government publications are constantly being updated web sites were the most appropriate sources for this information.

Search terms and key words applied:

- carbon monoxide
- nitrogen dioxide
- VOC or volatile organic compound
- energy efficient home
- ultrafine
- particles
- health
- gas stove or gas cook$ or gas heat$ or gas appliance
- combustion
- biomass
- indoor air quality
- home
- zero carbon

For an idea of how many search hits were given for individual key words and phrases, the following were searched in Scopus using search fields of the article title, the abstract and the keywords, their number of hits are given. All Scopus searches were limited to exclude studies published before 1990 and those that were not in English were also excluded.

- “Carbon monoxide” – 49,971 hits
- combustion - 104,371
- gas stove OR gas cook$ OR gas heat$ OR "gas appliance" - 66,425 hits
- “energy efficient home” – 53 hits

($ indicates any other letters that may follow the principal term, such as for gas heat$, gas heating, gas heaters and gas heat will all be found in the search.)

Combining searches and adding keywords and phrases to the search narrows the number of hits to give more specific and useful list of results from the search, the most effective searches are given:

Carbon monoxide and indoor air:

- carbon monoxide AND air quality OR indoor air

This search gives 2,421 hits. This search was combined with the following string:

- AND (home OR dwelling OR house) - 215 hits

Gas combustion products:

- “gas stove” OR gas cook$ OR gas heat$ OR "gas appliance" OR combustion

This search gives 98,475 hits and was combined with the following strings:

- AND (home OR dwelling OR house) AND (“carbon monoxide”) – 108 hits
- AND (home OR dwelling OR house) AND (“nitrogen dioxide”) - 64 hits
- AND (home OR dwelling OR house) AND (particle OR particulate OR ultrafine) - 181 hits
- AND (home OR dwelling OR house) AND (VOC OR volatile organic compound) - 28 hits

Indoor carbon monoxide modelling:

- “indoor air” AND "carbon monoxide" AND model$

This string generates 90 hits and was combined with the following:

- AND (home OR dwelling OR house) – 26 hits

IAQ and energy efficient homes:

- indoor air quality – 6,269 hits (search 1)
- indoor air pollution OR indoor air pollutant – 15,160 hits (search 2)
- “energy efficient” AND indoor air AND (home OR dwelling OR house) – 53 hits (search 3)

Search 1 and search 3 were combined to give 28 hits. Search 2 and search 3 were combined to give 13 hits.

Titles and abstracts of the hits generated from searches were screened to assess their eligibility for inclusion in the review. Hard copies of studies that were potentially relevant were retrieved for further assessment. Grey literature such as manufacturer’s information for appliances and manuals were found as well as a range of information internet sites.

Appendix B Standard methods for measurement of air quality

B.1 BS EN 50291:2001

Electrical apparatus for the detection of carbon monoxide in domestic premises — Test methods and performance requirements.

The alarms have criteria for the audio and visual alert, where once activated the alert will remain until CO concentrations drop below 50 ppm. Table B-1 summarises the time periods and concentration boundaries when alarms should activate.

Table B-1: Set points of CO alarm activation

(Source: British Standards Institution, 2001a, p.7)

CO Concentration	No alarm before	Alarm before
30 ppm	120 minutes	-
50 ppm	60 minutes	90 minutes
100 ppm	10 minutes	40 minutes
300 ppm	-	3 minutes

European standard 50292:2002, “Electrical apparatus for the detection of carbon monoxide in domestic premises. Guide on the selection, installation, use and maintenance”, is to be used in conjunction with BS EN 50291. This standard takes into account that households vary and gives guidance on where and where not to install CO alarms. It advises that ideally an alarm should be installed in every room containing a fuel burning appliance describing the best location to install the device and where they should not be installed, such as areas where it could be obstructed and affected directly by ventilation, as well as the ideal height and distance from appliances.

B.2 BS EN 14626:2005

Ambient air quality — standard method for the measurement of the concentration of carbon monoxide by non-dispersive infrared spectroscopy, (British Standards Institution, 2005a).

This standard document details the method for determination of the concentration for CO in ambient air via a continuous non-dispersive infrared (NDIR) analyser, giving suggestions for minimum criteria and suitability for fixed site measurements where monitors are put through type approval tests, to test uncertainty under the conditions of use. There is no specific guideline for the exact sampling method or equipment, but inlets should be constructed to prevent rainwater entering, be of minimum length and consist of material which will not interact with the sample so that the total loss of CO concentration due to the sampling system will be less than 2%. This standard discusses methods of maintenance, cleaning, filtering for particulates, the use of a pump, dealing with interfering gases and corrections. The detection limit should be greater than or equal to zero and should not span more than 5% from the last certified value.

B.3 BS 7967 series

Carbon monoxide in dwellings and the combustion performance of gas-fired appliances. This standard is issued in four parts:

BS 7967-1:2005 Part 1: Guide for identifying and managing sources of fumes, smells, spillage/leakage of combustion products and carbon monoxide detector activation.

BS 7967-2:2005 Part 2: Guide for using electronic portable combustion gas analysers in the measurement of carbon monoxide and the determination of combustion performance.

BS 7967-3:2005 Part 3: Guide for responding to measurements obtained from electronic portable combustion gas analysers.

BS 7967-4:2007 Part 4: Guide for using electronic portable combustion gas analysers as part of the process of servicing and maintenance of gas-fired appliances.

The objective of the series of standards, which is aimed at gas operatives, is to protect the health and safety of the occupants and the property, locate all gas burning appliances and to identify if the appliances are safe or if there are any concerns.

Part 1 (British Standards Institution, 2005b), gives guidance for identifying and managing sources of combustion products, noting that with the exemption of cookers, which may produce short term peaks in emissions especially on ignition of grills, if CO levels exceed 30 ppm, appliances should be turned off and occupants should vacate the dwelling and ventilation via windows and doors is advised. A flowchart for the procedure of CO investigation can be found in this standard along with in-depth guides and information on ventilation and flue checks. Appliance checking to be carried out by gas operatives through visual checks and the identification of suspected CO producing appliances is explained.

Part 2 (British Standards Institution, 2005c) discusses the use of electronic analysers, they should measure and display CO in ppm and for readings of 20 ppm or below, accuracy should be at least ±3 ppm and for above 20 ppm the accuracy should be at least ±5 % of the instrument reading. The equipment recommendation states analysers should measure either just CO or CO and oxygen and calculate the level of CO_2 from the measured levels of oxygen. There are guides for recommended ways to measure the three different types of appliances: flueless, open flue and room sealed appliances. The testing procedure for this standard is not suitable for monitoring CO in the home of an occupant in their natural setting as it requires only one combustion appliance to be operated at a time in order to monitor the rooms CO.

Guidance for measurements obtained via methods from part 2 is given in part 3 (British Standards Institution, 2005d), of the series. It also is worth noting that the detection of sources as described in part 2 is for rectifying faults and may not be appropriate where absolute measurement values are required, such as relating levels to health hazards. The standard also makes reference to the adoption of the WHO air quality guidelines for Europe, with average levels of 10

ppm not to be exceeded over an 8 hour period but does concede that short term peaks may be higher when appliances are used and other such sources such as smoking and car exhaust emissions are present, but at 30 ppm, occupants should be evacuated. Part 4 (British Standards Institution, 2007a), gives guidance for gas operatives on the use of an electronic portable instrument for determination of the level of servicing required and confirming satisfactory combustion following servicing and maintenance.

B.4 BS EN ISO 16000

B.4.1 Indoor air - Part 1: General aspects of sampling strategy

It is recommended that the WHO guidelines are referred to when interpreting if the indoor air measurements are satisfactory. Part one deals with the significance of the purpose, when, where, how often and over what periods of time monitoring is to be performed to devise a sampling strategy which will vary depending on the objective, environment and special characteristics of the indoor environment. Objectives may include investigations of complaints, determination of exposure, investigation to see if guidelines are maintained, investigating observed or suspected health effects and testing effectiveness of remedial treatment.

Two approaches for sampling are described as either onsite measurements using manageable instruments with subsequent analysis performed in the laboratory or sampling and analysis carried out onsite by direct reading instrumentation. A formula for how the change in concentration with time is affected by variables such as the increase in concentration due to a source and penetration of outdoor air and also a decrease in concentration via ventilation and sorption is also included.

The procedure for sampling is described as long term if it is more than several hours and short term up to an hour of sampling. Requirements for residential monitoring include the need to be relatively noise free, a sampling rate that should not interfere with the ventilation rate and when positioning the monitor consideration should be taken into account for the possibility of the

concentration of the indoor air not being homogeneous. The hourly sampling volume should be less than 10% of the ventilation rate and diffusive methods are preferred to that of active for long term sampling procedures.

The length of time for the sampling should take into account the variation in concentration of air pollutants with time. Unless of specific interest, ventilation of sources such as tobacco smoke and chemical vapours should be applied and measurement undertaken at a fixed time after the building is closed. Change in ventilation, such as opening a window should decrease the concentration of pollutants but may disturb previously established equilibrium, so for short term sampling several hours should be allowed to establish equilibrium, provided that there are no objections from the occupants.

Information may be lost if the sampling time is unsuitable. Short term sampling is usually for measuring extremes in conditions and long term is usually for monitoring pollution under normal conditions. The conditions of use and occupancy of the room should be noted and as much information on room parameters that can influence results should be provided.

If monitoring indoor pollutants from intermittent sources, the sampling time would depend on the objective, such as peak exposure or average exposure. Buildings with heating, ventilation and air-conditioning (HVAC) may have undesirable emissions from this system and so the state of maintenance of the system should be included in the report.

The location of sampling should account for spatial variation and in private dwellings should not affect the use or occupant behaviour. The centre of the room is considered to be the most suitable location but if this is not acceptable, the monitor should be no closer than 1 m to any wall and about 1 - 1.5 m above the floor. The equipment should be protected from human intervention and areas the samplers should not be placed are in the sun, nearby a heating system and near draught or ventilation sources.

With cooking stoves, thermal movement of air leading to marked concentration gradients may result in the need to subdivide a room into different areas and simultaneously sample the areas. Parallel outdoor air measurements and information on wind direction and velocity may also be of interest.

B.4.2 Part 2: Sampling strategy for formaldehyde (ISO 16000-2:2004)

Part 2 of this series (British Standards Institution, 2004a) is for aiding measurements of formaldehyde in indoor air. Several methods for formaldehyde measurements are acknowledged with active sampling preferred for short term measurements (described in part 3) and diffusive samplers are the preferred method for long term measurements (described in part 4).

B.4.3 Part 3: Determination of formaldehyde and other carbonyl compounds — Active sampling method (BS ISO 16000-3:2001)

Part 3 (British Standards Institution, 2001b) details an active sampling method and is applicable to formaldehyde and other carbonyl compounds with a concentration range of 1 µg m^{-3} to 1 mg m^{-3} and can be used for long and short term measurements, described as 1 – 24 hours and 5 – 60 minutes respectively. The compound is collected by passing air through a reactive medium coated with 2,4- dinitrophenylhydrazine (DNPH), with use of a pump, which converts them to their corresponding hydrazones which can be efficiently recovered and measured with high sensitivity, precision and accuracy. Subsequent analysis is performed with high performance liquid chromatography (HPLC) equipped with UV absorption or diode array detectors. Part 3 also instructs on preparation of sampling cartridges, sample collection, sample analysis and identifies ozone and NO_2 as known interferences.

B.4.4 Part 4: Determination of formaldehyde — Diffusive sampling method (BS ISO 16000- :2004)

Part 4 (British Standards Institution, 2004b) details a method for diffusive sampling, which may also be used to monitor personal exposure, involving a DNPH coated desiccant to react with formaldehyde, solvent desorption and subsequent analysis with HPLC equipped with a UV detector as in part 3. The method is specific to formaldehyde in indoor air with a range from 0.001 mg m^{-3}

to 1 mg m^{-3} for a sampling period of 24 - 72 hours to give a time-weighted average result. In parts 3 and 4, methods from preparations to relevant calculations and reports are included.

B.4.5 Part 5: Sampling strategy for volatile organic compounds (VOCs) (BS EN ISO 16000-5:2007)

Part 5 of the indoor air series (British Standards Institution, 2007b) is an aid in planning VOC measurements in indoor air describing basic aspects to be considered for a sampling strategy and also defines VOCs, their sources and importance of a measurement strategy to ensure results are valid.

B.4.6 Part 6: Determination of volatile organic compounds in indoor and test chamber air by active sampling on Tenax TA sorbent, thermal desorption and gas chromatography using MS/FID: (ISO 16000-6: 2004)

A method for measuring VOCs in indoor air or test chamber air using Tenax TA sorbent tubes with subsequent analysis by thermal desorption and GC is described in part 6 of the indoor air series (British Standards Institution, 2004c). In this standard, the reagents, materials and apparatus required for this method are given, in which a pump is required to be connected to the sorbent tube to draw in the sampled air. The analysis is also described in which the collected VOCs are thermally desorbed from the sampling tubes and separated in the GC column and detected by flame ionisation and/or mass spectrometric detector. Identification of single VOCs and concentration of analytes in the sampled air is described and how to compile a test report and how to employ an appropriate level quality control procedures. The annex of this standard provides examples of commonly emitted VOCs with their boiling points.

B.4.7 Part 15: Sampling strategy for nitrogen dioxide (NO_2)

Part 15 of the Indoor air standard series (British Standards Institution, 2008b) describes long term and short term (up to an hour) measurements. Generally manual analytical methods are used for short term measurements and diffusive samplers for long term measurements, both methods use similar methods in the analysis. Continuous monitoring instruments can be used for either short or long

term measurements, but diffusive is preferred over continuous monitoring instruments for long term measurements as it is more cost effective and noise may rule out its use indoors over long periods of time.

For short term measurements, where continuous methods are used, time resolution of less than 20 seconds is required. Alternatively, manual methods using suction pumps can be used where NO_2 from the air is passed through a sorbent. The manual methods would not give specific peak concentrations as these would be integrated in the averaged value over the specified time.

For long term use, diffusive samplers are recommended as these are unobtrusive and therefore useful for use in dwellings as well as personal exposure monitors. These samplers should be kept out of contact with UV light as NO_2 will react in its presence. With the use of diffusive samplers the performance characteristics, method, conversion equation and uncertainties should be documented. The purpose of measurement should be defined also, such as a research study and the type of active sources and environment during sampling should be documented.

Height of samplers should be about 1.5 m and should be at least 1m away from walls. Airflow measurements may be useful and sampling plans should always include measurements in the main area occupied by room users. When diffusive samplers are used, at least two should be used per room.

B.5 16017 - Indoor, ambient and workplace air — Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography

Parts 1: Pumped sampling (EN ISO 16017−1:2000)

Part 2: Diffusive sampling (EN ISO 16017−2:2003)

General guidance for sampling and analysis of VOCs is given in both parts 1 and 2 and is applicable to a variety of VOCs. Part 1 is appropriate to a

concentration range of approximately 0.5 µg m^{-3} - 100 mg m^{-3} for individual compounds and part 2 is appropriate for a concentration range of 0.002 mg m^{-3} – 100 mg m^{-3} for an exposure time of 8 hour or 0.3 µg m^{-3} - 300 µg m^{-3} for an exposure time of up to 4 weeks. Both parts give recommended sorbents for sampling.

Part 1 (British Standards Institution, 2000) uses active sampling by drawing air through sorbent tubes to obtain VOC whereas part 2 (British Standards Institution, 2003) uses passive diffusive sampling, exposing the sorbent to air where VOCs diffuse into a tube. The analysis is the same in both and involves desorbing the sample with heat and passing it through a gas chromatograph with an appropriate detector such as a flame ionisation detector. The different criteria and sampling methods are discussed in the two standards, such as reagents, materials, apparatus and procedures. Calculations and interferences are discussed, with known interferences in both methods being identified as VOCs with very similar retention time which can be minimised by the selection of the column and analytical conditions. For diffusive sampling, ozone and oxides of nitrogen may react with certain types of diffusive samplers.

Appendix C Testing of carbon monoxide monitors and pilot studies

C.1 Testing of carbon monoxide monitoring equipment

C.1.1 Aims

- Assess the correlation between the different CO monitors.
- Develop a procedure to periodically check the monitor performance.

C.1.2 Method

The CO sensors response was tested against BOC certified gas obtained from BOC, Special Gases Division. The gas supplied was 30 ppm CO in synthetic air in an AZ cylinder of 1.2 l capacity (200 bar) fitted with BS4 valve outlet and HP1500B series single stage regulator for non-corrosive gases with ¼ inch compression fitting. The certified values have an uncertainty of ≤5%, and have been analytically determined using standards traceable to internationally recognised reference materials.

Sensors were exposed to CO in gas bags that were made from Nalophan (polyethylene terephthalate, PET) tied at both ends with cable ties with the monitors placed inside (Figure C-1). Tygon tubing was used to extract or deliver gas flow to/from the bag containing the sensors with an inner diameter of ¼ inch and an outer diameter of ¾ inch and a wall of $^{1}/_{16}$ inch. Air was evacuated via suction pump before use. The bags were disposed of after each use.

Nalophan is generally used for food storage bags, but has been previously used for gas storage. It was used due to its availability and relatively low cost in comparison to other bags used for gas storage such as Tedlar. For the Nalophan bag, it would be more efficient to dispose of the bag after single use and make up a new bag rather than try and clean for re-use. Nalophan has previously been used to sample odourous chemical concentrations and it was reported that the concentrations were relatively stable between 4 – 12 hours after sampling (Van Harreveld, 2003). CO is a relatively unreactive gas and is

therefore thought not to react with the bag, but over time is expected to diffuse out. It is also unsure how airtight the bags are with the cable ties sealing the ends and the rate of the oxidation of CO on the surface of the metal oxide sensor is unknown. Data uploaded from the monitors was analysed using Microsoft Office Excel 2007.

Figure C-1: Test bag with loggers sealed inside

A paired two-sample t-test assuming equal variances was calculated in the Analysis ToolPak on Microsoft Excel 2007 to assess if there was a significant difference in the readings for the two ICOMs and the two ELs (where applicable). For this, 15 minute averages were calculated from the original logged data to test the hypothesis that there was no significant difference between same branded monitors. If there was no significant difference, the average of the two same branded monitors would be compared to the average of the other brand to see if there was a significant difference. The average mean difference was also calculated to assess how closely the monitors readings agreed and the 95% confidence interval assuming a normal distribution of differences was calculated, where it is expected that approximately 95% of the readings would lie between.

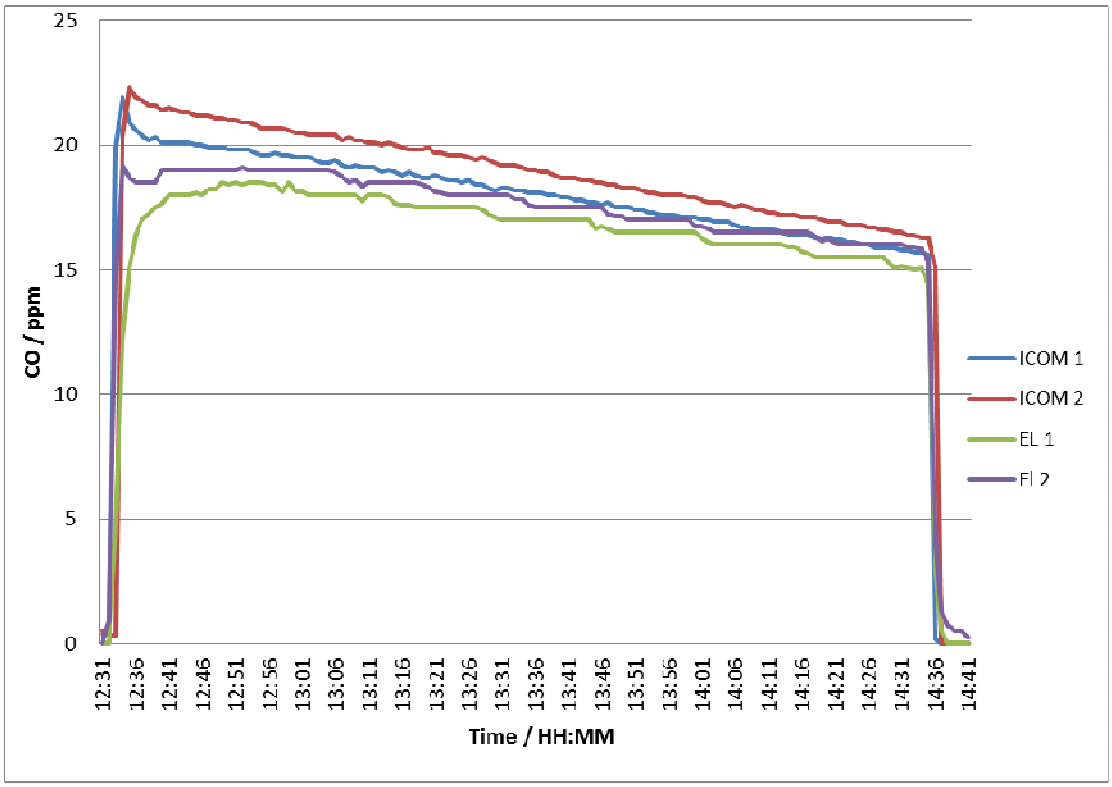
C.1.3 Test 1

The logging rate intervals were 10 seconds for both the EL loggers and 1 minute for both ICOM loggers in all tests. A 50 cm length test bag was made and two ICOMs and two ELs were inserted. They were left in the bag for two hours after approximately 2 l of CO had been pumped into the bag and the bag sealed. The data for the ICOM over the two hour period is shown in Figure C-2. Both ICOMs show a steady decrease in concentration and although the data readings are not identical the two lines are parallel and show the same overall trend, showing their responses are similar. The EL data also shows a similar trend. Both of the ICOMs have maximum peaks above 20 ppm (20.9 and 22.3 ppm) whereas the EL both peaked below 20 ppm (19.5 and 18.5 ppm), as observed in Figure C-2. Close positive correlation was observed between the different monitors (Table C-1). 1 minute averages were calculated from the 10 second recorded data points for the EL in the comparison.

Table C-1: Correlation of monitors used in test 1

	ICOM 1	ICOM 2	EL1	EL2
ICOM 1	1	-	-	-
ICOM 2	0.94	1	-	-
EL1	0.96	0.98	1	-
EL2	0.99	0.97	0.98	1

Figure C-2: Concentration of CO over 2 hours spent in bag for the ICOM and EL loggers



There was no significant difference between ICOM 1 & ICOM 2 (t = 0.49, df = 16). The average difference between the ICOMs was 0.8 ppm (95% confidence interval = 0.44 – 1.16) and the standard error of the mean (SEM), was 0.186.

There was no significant difference between EL1 & El 2 (t = 0.51, df = 16). The average difference between the ELs was 0.8 ppm (95% confidence interval = 0.45 – 1.15) and the SEM was 0.179.

There was no significant difference between the average of both ICOM & the average of both EL (t = 0.73, df = 16). The average difference between the averages of both sets of monitors was 1.2 ppm (95% confidence interval = 1.60 – 0.80) and the SEM was 0.202.

C.1.4 Test 2

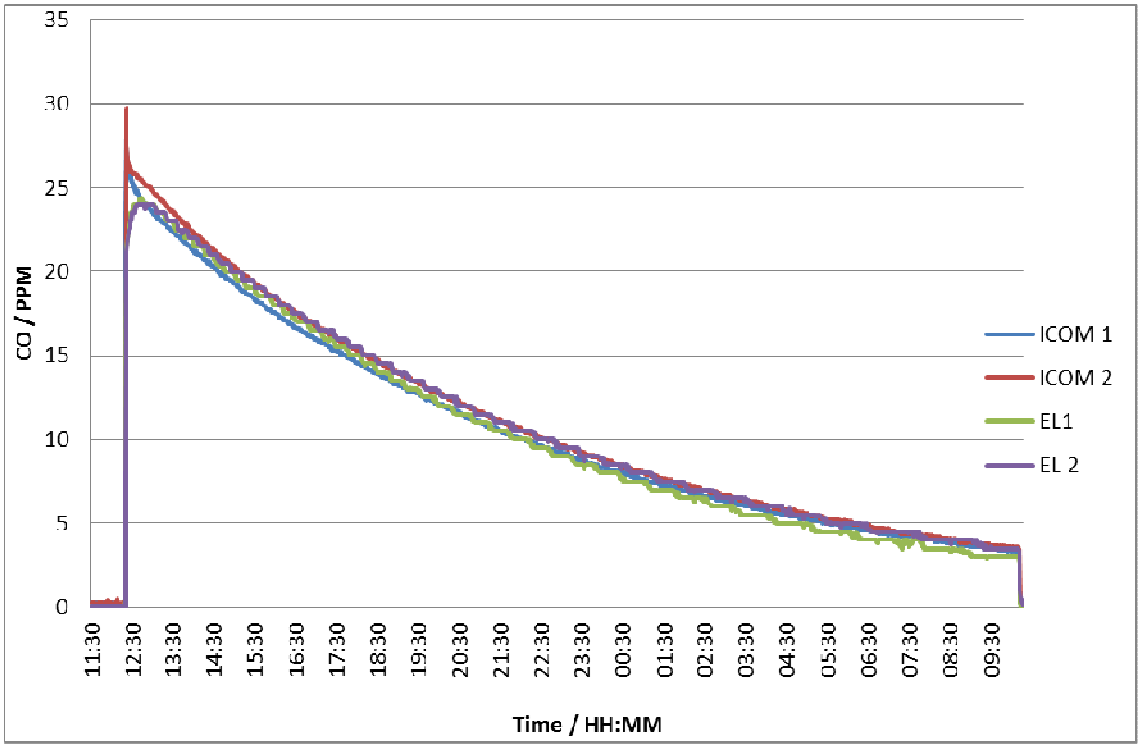
The same array of monitors was tested in zero grade air to see if there was any response to this. A 60 cm bag was used and preferred to a 50 cm length bag, (it was found that the 50 cm was hard to tie up due to spatial constraint), which could hold approximately 3 l of gas. The two ELs gave 0 ppm readings

throughout the 19 hours in the bag and the ICOMs did not exceed 0.3 ppm and on average were both 0.1 ppm over the 19 hours.

C.1.5 Test 3

The monitors were all tested again in 30 ppm CO in synthetic air in a 60 cm bag, but were left for approximately 22 hours. This allowed the response and linearity of the loggers at lower concentrations to be observed which were not reached in Test 1 over the shorter time of exposure. The two ICOMs seem to have a larger difference in value at the higher end of the concentration scale compared to the lower end Figure C-3, the difference at the higher concentration range is less than 6%.

Figure C-3: Concentration of CO over a day spent in bag for the ICOM and EL loggers



All of the CO loggers have the same trend in the chart, the EL have a less smooth curve which is due to their lower resolution of 0.5 ppm compared to the ICOM which has 0.1ppm resolution. One minute averages were also calculated for the EL which as previously mentioned were set at 10 second logging rates

so it was compatible for comparison with the ICOM. The four monitors for Test 3 were closely correlated (Table C-2).

Table C-2: Correlation of monitors used in test 3

	ICOM 1	ICOM 2	EL 1	EL 2
ICOM 1	1	-	-	-
ICOM 2	0.99	1	-	-
EL 1	1.00	1.00	1	-
EL 2	0.99	1.00	1.00	1

There was no significant difference between ICOM 1 & ICOM 2 (t = 0.58, df = 172). The average difference between the ICOMs was 0.5 ppm (95% confidence interval = 0.44 - 0.56) and the SEM was 0.031.

There was no significant difference between EL1 & El 2 (t = 0.54, df = 172). The average difference between the ELs was 0.5 ppm (95% confidence interval = 0.45 - 0.55) and the SEM was 0.024.

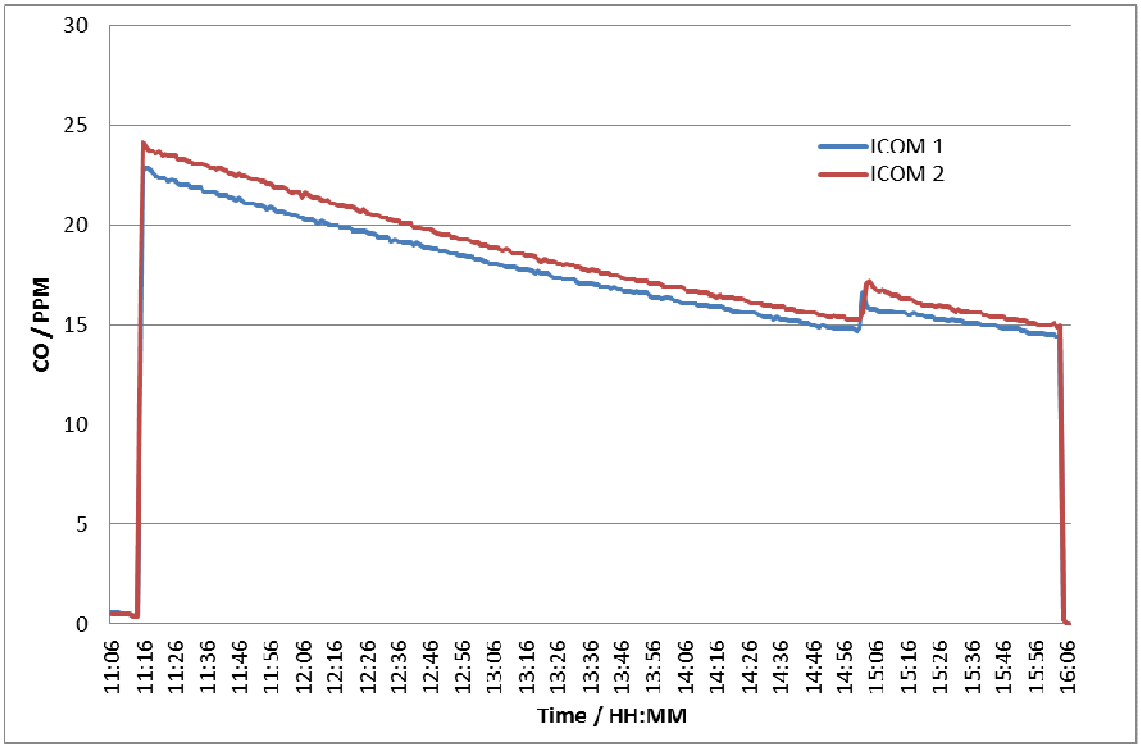
There was no significant difference between the average of both ICOM & the average of both EL (t = 0.12, df = 172). The average difference between the averages of both sets of monitors was 0.1 ppm (95% confidence interval = 0.18 - 0.02) and the SEM was 0.043.

C.1.6 Test 4

The two ICOMs were also used to compare with two Drager passive diffusive colorimetric tubes in a 60 cm bag. They were exposed for 5 hours in the bag, after 4 hours more CO was pumped into the bag to ensure that the Drager tubes had a readable concentration to read off in the short time of exposure. The tubes were read as soon as the bags were opened and both were approximately 100 $ppm.h^{-1}$, which for a 5 hour exposure period gives an average of 20 ppm. The ICOM data was uploaded and for the 5 hour exposure

period the two ICOMs read 17.0 ppm and 17.8 ppm. When the bags containing CO were opened, the monitors fell to below 0.5 ppm after a couple minutes for the ICOMs, Figure C-4 shows this pattern. The correlation coefficient for the two ICOMs in Test 4 is 1.00.

Figure C-4: Concentration of CO over ~5 hours spent in bag for the ICOM

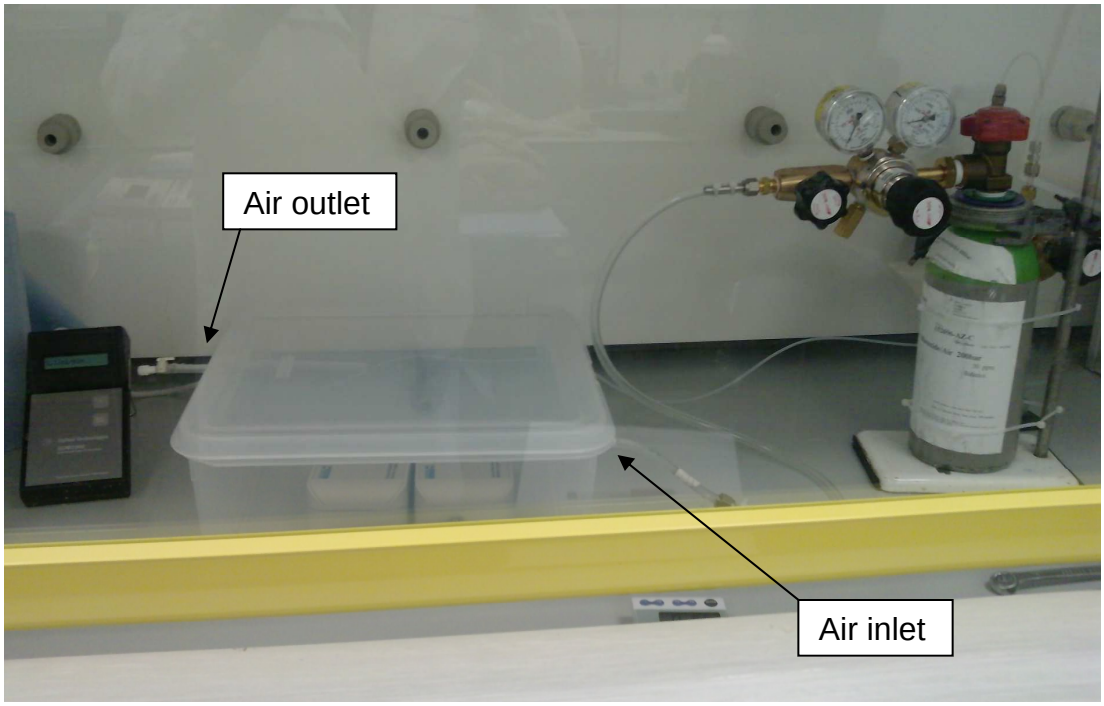


There was no significant difference between ICOM 1 & ICOM 2 ($t = 0.50$, $df = 40$). The average difference between the ICOMs was 0.7 ppm (95% confidence interval = 0.83 - 0.57) and the SEM was 0.066.

C.1.7 Test 5

In Test 5 a different approach was used, which was to have a constant flow of CO across the monitors in a sealed container in a fume hood (Figure C-5). CO was pumped through at 500 ml min^{-1} for 7 minutes and then left for a short while after where the flow of air leaving the box dropped to ~1 ml min^{-1}.

Figure C-5: A photo of the container with the monitors inside with the CO cylinder to the right and the flow meter to the left



The monitored CO in this test had the largest differences than in any of the other tests, as depicted in Figure C-6 and the correlation data in Table C-3.

Figure C-6: Concentration of CO in for the ICOM and EL loggers in the container

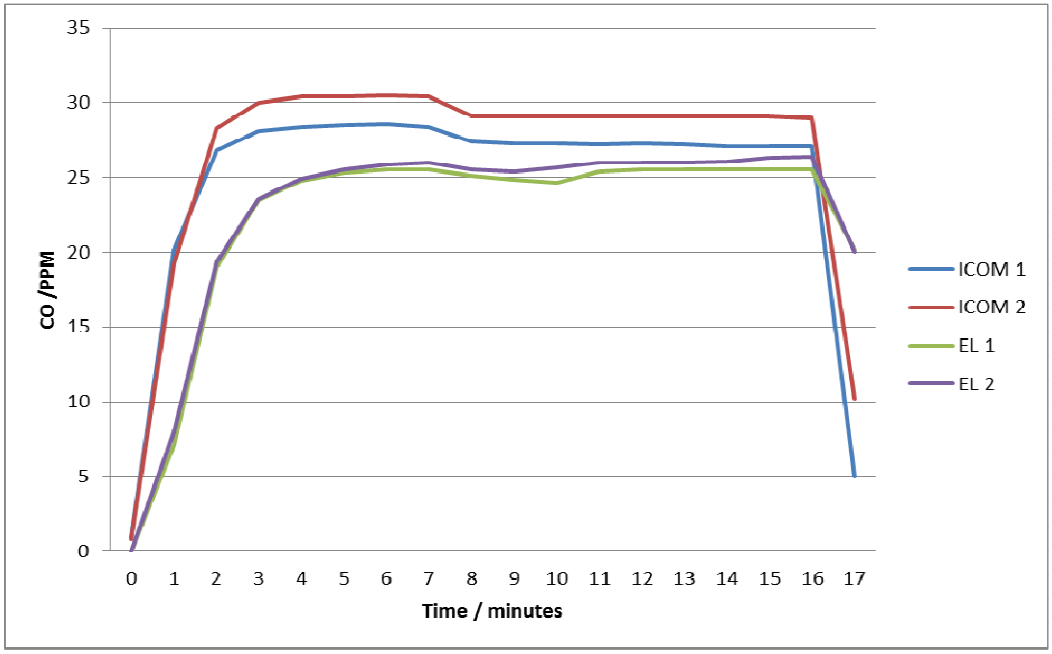


Table C-3: Correlation of monitors used in test 5

	ICOM 1	ICOM 2	EL 1	EL 2
ICOM 1	1	-	-	-
ICOM 2	1.00	1	-	-
EL 1	0.77	0.85	1	-
EL 2	0.78	0.86	1.00	1

One minute average data was used to calculate and compare the monitors in Test 5, which is what the ICOMs was set at and was calculated for the ELs. There was no significant difference between ICOM 1 & ICOM 2 (t = 0.66, df = 34). The average difference between the ICOMs was 1.8 ppm (95% confidence interval = 2.34 – 1.26) and the SEM was 0.276. There was no significant difference between EL1 & El 2 (t = 0.19, df = 66). The average difference between the ELs was 0.5 ppm (95% confidence interval = 0.35 - 0.65) and the SEM was 0.078.

There was no significant difference between the average of both ICOM & the average of both EL (t = 1.17, df = 66). The average difference between the averages of both sets of monitors was 3.0 ppm (95% confidence interval = 0.84 – 5.16) and the SEM was 1.102.

C.1.8 Conclusion

It is unclear whether the differences between monitors are experimental error or due to the placement and positioning in the bag. A real time CO monitor could perhaps have been used to check if the CO escaping the bag was doing so at a significant rate. Possible further work could be undertaken at ambient levels, such as a few ppm to further compare the response at lower concentrations which will more likely be observed during the monitoring in homes. Also work to test responses to typically known interferents could be carried out, although many are filtered and hydrogen is the only known interferent of the ICOM

electrochemical cell and for EL hydrogen, ethanol and NO_2, where the NO_2 at 30 ppm would give a response of less than 10 ppm. The typical error of the EL from the specification is ±4; the ICOM does not supply this in their specification.

The tests have successfully tested the response and correlation of the four CO monitors which are to be used in monitoring CO in the home. There were no significant differences between the same types of monitors or between the different brands of monitors in the tests used. All data was comparable from one monitor to the next and all monitors showed the same trend in the rise and fall of concentrations. Lascar will unable to detect the general background levels in homes (less than 0.5 ppm) but should detect elevated CO levels associated with indoor sources.

C.2 Detailed results of air quality measurements in Pilot homes

C.2.1 H1

H1 is located in a suburban area with moderate traffic. Double glazed windows with trickle ventilators were located throughout the home. There is no cooker hood fitted in the kitchen. There was no schedule for water heating. No forms were available at the time of the monitoring and therefore times of activities were noted on paper. One ICOM, with a logging rate of 1 minute, was used and the data from the home was collected during only one period where a cooking activity took place in the kitchen on a weekday. The home questionnaire was later handed out to retrieve information about the home.

In H1, monitoring was carried out for approximately 1.5 hours, during which cooking activity involving gas hobs and a gas oven occurred. The monitor was switched on and off by the participant prior to cooking and for a small period after cooking. The maximum peak (Table C-4) was observed approximately 5 minutes after the gas hob had been switched off and the gas oven was still on.

Table C-4: Summary of CO data from the kitchen of H1

	ICOM 1
Maximum	4.6 ppm
Minimum	0.3 ppm
Average	3.2 ppm
Standard Deviation	1.6 ppm

C.2.2 H2

H2 is located in an urban area with moderate traffic. There were no trickle ventilators in this house which had double glazing throughout. Incense was often burned and water heating was not scheduled. The primary cooking fuel was natural gas which fuelled the hob, oven and grill; these were greater than 10 years old. A cooker hood which extracts air to the outside is also fitted. Monitoring for H2 was observed on two separate occasions, during the first period of monitoring, the logging was carried out for approximately 38 hours over a weekend. The monitors used were one ICOM CO logger and two EL-USB-CO (EL) CO loggers both set at 1 minute log rates. All the monitors were placed on a kitchen worktop. On the second instance, the same loggers and locations were used for approximately 35 hours. The activity diary of the participants' whereabouts and windows opened throughout the house was not used in the first period of monitoring but was issued in the second period.

It was found that the ELs at 1 minute logging rates did not measure CO concentrations accurately. An expected baseline of readings for background levels, i.e. in the middle of the night when no activity will affect measurements, is expected to be low and of about 0.5 ppm or less. EL1 had a baseline of 0 ppm and did not respond until the levels were elevated with the use of the gas grill and the other EL 2 had a baseline of 3 ppm of CO. The ICOM and EL results from first and second monitoring period (P1 and P2) are shown below. A

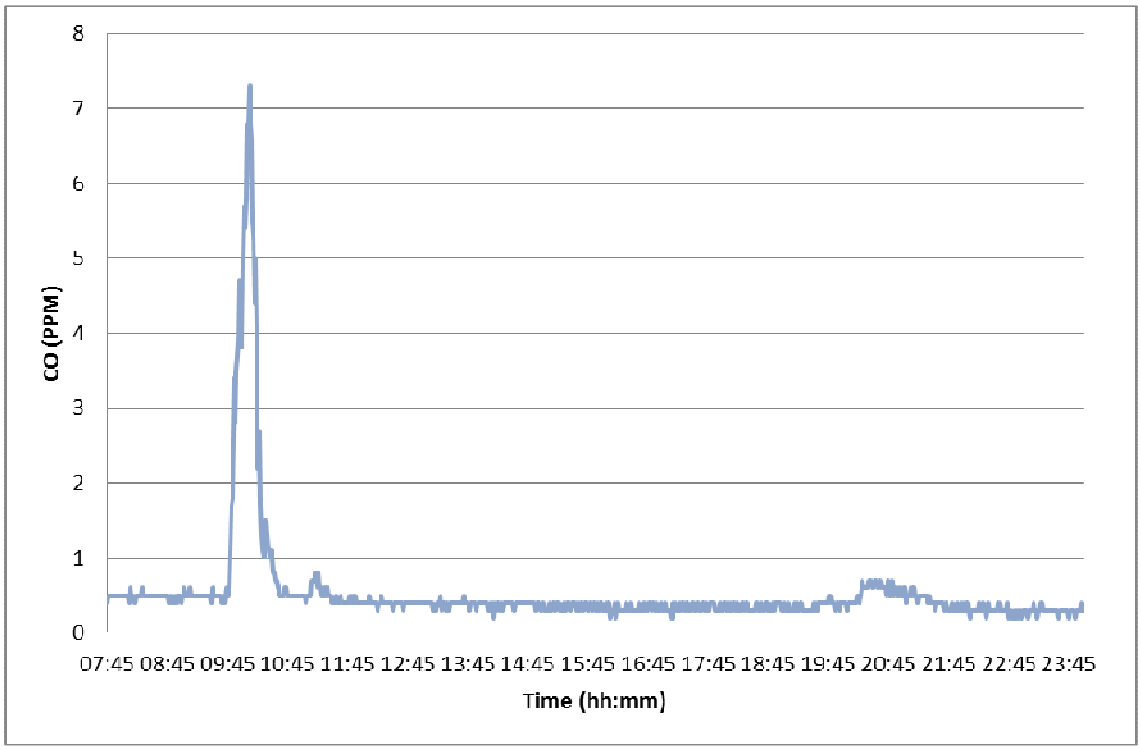
summary of the CO data for both monitoring periods is summarised in Table C-5.

Table C-5: Summary of CO in H2 from ICOM and EL for monitoring period 1 (P1) and period 2 (P2)

	ICOM P1	EL1 P1	EL2 P1	ICOM P2	EL 1 P2	EL 2 P2
Maximum	7.3 ppm	1.5 ppm	9.0 ppm	10.1ppm	4.0 ppm	11.5ppm
Minimum	0 .0 ppm	0.0 ppm	0.0 ppm	0.0 ppm	0.0 ppm	0.0 ppm
Average	0.4 ppm	0.0 ppm	3.0 ppm	1.1 ppm	0.0 ppm	3.6 ppm
Standard Deviation	0.6 ppm	0.1 ppm	0.6 ppm	1.4 ppm	0.3 ppm	1.3 ppm

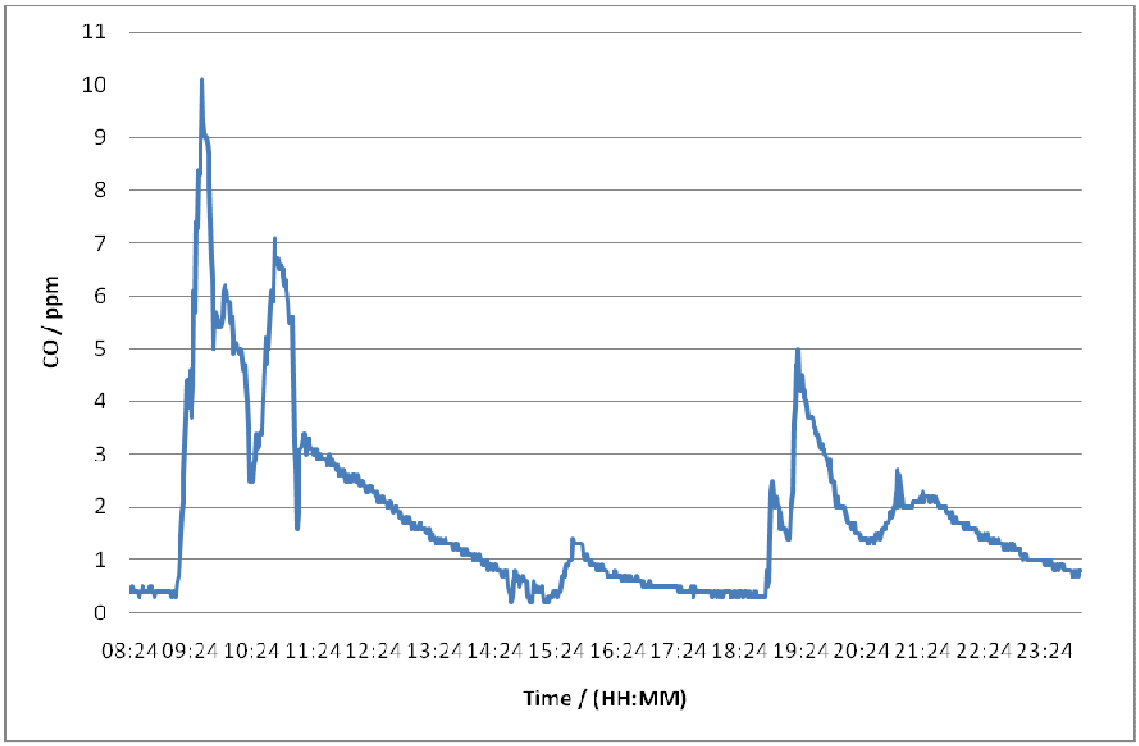
For P1, the gas grill was associated with the maximum level of CO found in the kitchen, with 7.3 ppm being observed just after an approximate 30 minute grill use on the first day of monitoring. On the second day the grill being used observed a maximum of 5.3 ppm with an external door in the kitchen open. The oven was used on four occasions over the monitoring period for a maximum of 2 hours; the level of CO did not exceed 1 ppm on any occasion of oven use. Figure C-7 shows the CO pattern for the ICOM in P1 on the first day (between 07:45 – 00:00), the peak is due to use of the gas grill. The level of CO monitored was generally below 1 ppm for both days.

Figure C-7: Chart of CO against time for kitchen Day 1 in H2, monitoring Period 1



For P2, the gas grill was associated with the maximum peak in CO found. On one occasion an oil lamp and incense stick were burnt in the kitchen in the same time period observing a 2.7 ppm maximum over this period. Half an hour after grill use, a single gas hob ring was used and a maximum of 5.0 ppm was observed, which may have been lower if not for the grill as the level had not fallen to the background level before the hob was used. Figure C-8 shows the trend in CO observed from the ICOM in the first day of monitoring for P2 (8:30 – 00:00). More activities in the kitchen were reported in P2 on the first day of monitoring than in P1. The CO concentrations can be seen to be over 1 ppm for the majority of the day. The three biggest peaks occur with reported use of the gas grill during day 1. For day 2, the two biggest peaks observed are from two separate uses of the gas grill.

Figure C-8: Chart of CO against time for Day 1 in H2, monitoring period 2



C.2.3 H3

H3 was located in a rural area with light traffic. This house had an attached garage used to store a motor vehicle. Double glazed windows were located throughout the home, some with trickle ventilators fitted. A scheduled daily water heating pattern was in effect, with 2 hours of operation between 6 am – 9 am and 2 hours between 4 pm – 10 pm. The cooker was approximately 10 years old and there was no cooker hood fitted. Incense / candles were regularly burned. The monitoring period was approximately 24 hours on a weekday. The monitors used were two ICOMs, two ELs, the PID and the UPC. The logging rates for the UPC and PID was 1 second, the EL logging rate was set at 10 seconds and the two ICOMs both had different logging rate of 1 minute and fifteen minutes. All monitors were located in the kitchen. The UPC and PID were turned off after approximately 5 hours.

The EL were set to 10 second log rates and did not record any values above 0 ppm throughout the monitoring period. This may be due to the fact that they have a lower resolution then the ICOM and the CO levels generated in this

house did not get elevated from the baseline, with averages recorded from the two ICOM monitors of 0.4 ppm and 0.5 ppm over the 24 hour period. The CO sensor on the PID appears to have been unreliable as it appeared to play up as it logged a maximum of 14 ppm when no activities were reported and the ICOM loggers monitored levels below 1 ppm at the same time period and location.

The gas hobs were used a couple times during the logging period but the values of the CO monitor did not deviate from the value prior to use. ICOM 1 was set at a 15 minute logging rate whilst ICOM 2 was set at a logging rate of 1 minute. The kitchen window/external door was shut throughout the monitoring except for one period during when the cooking activity occurred. The CO data is summarised in Table C-6.

Table C-6: Summary of H3 CO data

	ICOM 1	ICOM 2
Maximum	0.4 ppm	0.5 ppm
Minimum	0.1 ppm	0.1 ppm
Average	0.2 ppm	0.2 ppm
Standard Deviation	0.1 ppm	0.1 ppm

The UPC ran for approximately 4 hours. The maximum coincided with the use of the electric oven. The hob did not appear to impact the UFP levels, the data for which is summarised in Table C-7 along with the PID which ran for the same period of time, and the average shows that the level was generally low. In one instance the PID reading shot up to 45.3 ppm from a low level and returned back to a low level, all within a period of a minute during where no activity was reported.

Table C-7: Summary of H3 UFP and TVOC data

	UFP (pt cm^{-3})	TVOC (µg m^{-3})
Maximum	78,000	85,566
Minimum	4,240	0
Average	17,289	733
Standard Deviation	12,160	3,943

C.2.4 H4

H4 was in a suburb and had an attached garage which was used to store a motor vehicle. Double glazing with trickle ventilators was located throughout the house. The water heating was scheduled for half an hour between 6 am – 9 am and half an hour between 4 pm – 10 pm. A cooker hood which extracted air to the outside was also located in the kitchen. The monitoring was carried out for approximately 24 hours, using two ICOMs at 1 minute logging rates and two ELs at 10 second logging rates. The UPC and PID were also issued with one second logging rates. All were located in the kitchen, with the participant noting that the PID and one EL were located 1m from one side of the cooker, the UPC and ICOM at the other side, one EL 2m opposite the cooker and the final ICOM 2.5m away from the cooker.

Using the 10 second logging rates, the ICOMs and the EL readings seem to correlate better than observed previously with 1 minute logging rates. ICOM 1 and EL 1 were slightly further away (approximately 2 m) from the cooker than ICOM 2 and EL 2 (approximately 1 m). In this monitoring period, the hobs were only used once, with the user noting that the internal kitchen door and the external kitchen door and windows were shut with the cooker hood on throughout the duration of cooking, and also for a small period of time after cooking. During this period, where for approximately 10 minutes one hob was on then the following 10 minutes two hobs were on, peaks were observed from all monitors. A summary of the CO data is found in Table C-8. The UPC and the

PID were allocated to the user but due to technical difficulties with the equipment, no data was obtained.

Table C-8: Summary of H4 CO data

	ICOM 1	ICOM 2	EL 1	EL 2
Maximum	8.2 ppm	9.0 ppm	7.5 ppm	9.0 ppm
Minimum	0.8 ppm	1.1 ppm	0.0 ppm	0.0 ppm
Average	0.8 ppm	1.1 ppm	0.7 ppm	1.0 ppm
Standard Deviation	0.8 ppm	0.9 ppm	0.8 ppm	1.0 ppm

C.2.5 H5

H5 was located in a rural area of low traffic density. The home had plastic framed double glazing with trickle ventilators in all window frames and the ground floor was constructed with concrete beams. A cooker hood was located in the kitchen. The kitchen trickle ventilators were open throughout the monitoring period. The monitoring was carried out for almost 3 days for the battery operated monitors used and the completion of the activity diaries. Two ICOMs, one in the kitchen and one in the living room, were set at 1 minute logging rates. Two ELs at 10 second logging rates were placed either side of the hob, (approximately 0.5 m) in closer vicinity than the ICOM in the kitchen which was approximately 2 m from the hob. The PID and the UPC were also used with one second logging rates both placed in the kitchen alongside the ICOM. Diffusive NO_2 tubes were placed in the garden, kitchen and the living room along with diffusive Drager CO tubes. The NO_2 tubes were exposed for nearly 3 weeks, whilst the Drager tubes were collected with the electronic monitors after 3 days.

The CO throughout the monitoring period was low, a peak of 1.1 ppm for the kitchen ICOM occurs approximately 30 minutes after a single hob is used for around 30 minutes and for the living room ICOM, the 0.7 ppm maximum occurs

around 1 hour after the cooking activity. EL2 has a maximum of 1 ppm which occurs around the same time period as ICOM 1 reaches its maximum peak of 1.1 ppm. EL1 did not record any data above 0 ppm. This period of cooking was the only time where any cooking was recorded during the monitoring period. The CO data is summarised in Table C-9.

Table C-9: Summary of H5 CO data

	ICOM 1	ICOM 2	EL 2
Maximum	1.1 ppm	0.7 ppm	1 ppm
Minimum	0.1 ppm	0.1 ppm	0 ppm
Average	0.2 ppm	0.3 ppm	0 ppm
Standard Deviation	0.1 ppm	0.1 ppm	0 ppm

The diffusive Drager CO tubes were taken out of the environment prematurely and did not obtain any readable value. The values for nitrogen dioxide were all well below the 40 µg m^{-3} recommended WHO annual mean (Table C-10) with the highest monitored valued recorded in the kitchen.

Table C-10: NO_2 Diffusive tube data for H5

Tube location	Length of exposure (hours)	Average NO_2 / µg m^{-3}
Garden	488	16
Kitchen	488	16
Living room	488	12

The UPC ran for approximately 7 hours and was turned on by the user and left running until the battery ran out. The PID started logging at the same time as the UPC (both sets of data summarised in Table C-11) and ran for 9 hours. The maximum TVOC and UFP levels coincide with the time of maximum for CO.

Table C-11 Summary of H5 UFP and VOC data

	UFP (pt cm^{-3})	TVOC (µg m^{-3})
Maximum	287,000	140,532
Minimum	3980	0
Average	22,335	2,496
Standard Deviation	41,922	6,814

Appendix D Protocol - “Risks to health of carbon monoxide and other combustion gases in energy efficient homes”

D.1 Introduction

This protocol will be used to obtain measurements of carbon monoxide (CO) and other combustion products, nitrogen dioxide (NO_2), ultrafine particles (UFP) and total volatile organic compounds (TVOC) concentrations in energy efficient homes. Indoor air quality (IAQ) in energy efficient homes is being studied as changes to UK building regulations could lead to new or increased concern about the indoor air that the occupant will be in contact with for a substantial amount of time per day, as people spend approximately 90% of their times indoors, and much of that is time in their home. Recent and proposed future changes in building regulations include increased air tight design and different methods of heating and ventilation to reduce energy consumption and help combat climate change.

The measurements of the combustion generated pollutants will be supported by questionnaires recording occupant behaviour, activity and details of the house. The data obtained will be evaluated, including by the use of models of IAQ to compare with health based guidelines for acceptable concentrations in air to assess possible risks to human health.

The aim of this protocol is to standardise the procedure for obtaining measurements of CO and other indoor air pollutants generated from combustion in energy efficient homes. The protocol is set out in stages. The main emphasis will be on CO generated by combustion in the kitchen and some habitable rooms by continuous monitoring but other associated pollutants are also of interest.

D.2 Stage 1 – House recruitment

Ideally a sufficient number of homes would be monitored to provide data representative of different forms of construction, regions, level of occupancy, season and type of combustion appliance. However the resources for the project limit the expectation to about 20 homes monitored for a few days each during the heating season. At this time of year combustion appliances will be most used and ventilation is likely to be lowest with windows and doors closed. The study requires an adult occupant in the household to complete questionnaires and an activity diary and to agree to the placement of small unobtrusive monitors for at least 24 hours.

To recruit volunteers to the study, letters will be sent to occupants of potentially suitable homes built since 2006 to invite their participation in the study (Section D.8). In particular, contacts in the Gas Safety Trust (the project sponsor), the Zero Carbon Hub and the Milton Keynes council where collaborations are already in place. In addition contact with other local councils or housing associations will be made as well as University staff/students to facilitate access to potential properties.

Control homes are not required as the measurements will be evaluated according to compliance with recommended indoor air quality guidelines for the selected combustion products. Comparisons will also be made with existing data from the literature concerning older homes.

D.3 Stage 2 – Inform the household

If the potential participant responds positively to the first letter, a second letter (Section D.9) will be sent giving further details of the study. Attached to this letter will be a guide describing the monitors (Section D.10) that will be used and suitable locations for their placement and also a participant information sheet with a consent form (Section D.11) to be read through and which must be signed to participate any further in the study. This will be collected during the next stage. The guide (Section D.10) briefly describes the use for the different types of equipment. The participant will then be contacted by the researcher to

arrange a time for a home visit to take place and participants will get a chance for queries to be resolved.

D.4 Stage 3 – Home visit

A suitable time and date will be arranged by telephone or e-mail contact. At the home visit, the monitors will be placed by the researcher in agreed locations in the kitchen, living room, a bedroom and garden. Associated forms to be filled in during the monitoring period will be handed out. These forms include a cooking diary which also records the type and approximate age of cooking appliance being used (Section D.13) and a diary to detail the time spent by the volunteer in different rooms and outside the house as well as some other activities that may influence IAQ such as smoking and ventilation (Section D.12). The completed consent form previously sent will be collected.

A questionnaire about the property, insulation, heating, cooking and information on the occupancy of the household will also be given to the occupant (Section D.14) along with a guidance sheet on how to fill in the questionnaire (Section D.15). This will be later collected by the researcher and any problems or queries can be sorted at that point. A form to be filled out for the diffusive tubes which require two weeks exposure will be left with the volunteer (Section D.16) with a date which the required tubes are to be sealed and posted back, it will be required by the volunteer to fill in the “closed” column.

Monitors will be placed out in accordance with Section D.10 but in an agreed location which best meets requirements of the study and is acceptable to the volunteer. Ideally, if all monitors are to be used, the following locations for the monitors are desired:

- 2 x ICOMs – kitchen and the living room.
- 2 x EL – kitchen and bedroom.
- UPC and the PID - kitchen, will require the participant to turn the PID off after a period of time, up to 8 hours.

- Drager tubes - bedroom, kitchen, living room and garden.
- NO_2 tubes - kitchen, garden, living and bedroom.

The researcher placing the monitors in the home may be accompanied by a fellow researcher but if the researcher is working alone then this protocol for lone working and good working practice will be followed:

- The researcher will leave contact details with co-workers.
- The schedule for the home visit will be given to co-workers.
- If there is a change of plan to the schedule, then the lone worker will contact a co-worker to notify them.
- After the scheduled monitoring has taken place, the lone worker will report back to a co-worker to confirm that everything is satisfactory.
- The researcher will have a digital camera to record images in the unlikely event of any damage being caused.
- If driving, the car will be covered by appropriate fully comprehensive insurance cover.
- The journey of work planned will be completed in a normal working day.
- The researcher will not be present in a volunteer's home unless an adult occupant of the household is also present.

D.5 Stage 4 – Collect back monitors

Two days later at an arranged time, the battery operated monitors will be collected. The questionnaire (Section D.14) given in the initial home visit will also be collected and any difficulties or queries will be addressed. If the NO_2 / Drager / VOC tubes are used, these require being posted back two weeks after placement along with the completed diffusive tubes monitoring form (Section

D.16). A prompt by phone or e-mail will be given to remind the participant and a pre-paid envelope will be provided for these diffusive tubes.

D.6 Stage 5 – Obtain and analyse results

The results for the NO_2 tubes will be obtained by sending them off for analysis to a commercial laboratory and receiving the results via email. The Drager tubes will be read by the researcher as soon as possible after collection. The diffusive tubes (Drager and NO_2) will give single values for an average over the time period of exposure. The electronic equipment will have their collected data uploaded to a computer for analysis by the researcher. No names or address will be stored on computer and homes will be coded by letters (e.g. Home A), where the code will only be known by the researcher and supervisor.

D.7 Stage 6 – Inform the household of results

Once analysed, the results will be given to the participant and will fall into three scenarios:

- Scenario one – the pollutant concentrations are below WHO guidelines
- Scenario two – the pollutant concentrations are above WHO guidelines
- Scenario three – CO concentrations are above workplace exposure limits.

For scenarios one and two, letters will be sent out to inform the household of the monitoring results (Sections D.17 and D.18). For Scenario three, a standardised phone call will be issued (Section D.19). Occupational exposure limits are not available for TVOC and NO_2 concentrations.

D.8 Pre-study letter: invitation

IEH
Cranfield Health
Vincent Building
Cranfield
MK43 0AL
Bedfordshire
England
Tel +44 (0) 1234 75 8300
Fax +44 (0) 1234 758380
www.cranfield.ac.uk/health

Date

To the occupant; Invitation to participate in a study of air quality in your home

I am a researcher at the Cranfield University Institute of Environment and Health investigating air quality in energy efficient homes. My particular interest is the possible health effects of carbon monoxide and other pollutants produced by the burning of fuel (gas, coal, wood etc.).

As part of my study I am seeking volunteers who would allow me to place some small and unobtrusive air quality monitors in their home. These monitors would be located in the kitchen, living room and main bedroom. These monitors are battery powered and quiet in operation and will not interfere with your daily activities. It would also be required that you fill in an activity diary, which includes noting your cooking activities and ventilation pattern over two monitoring days. The total duration of your involvement will be around two weeks.

All participants in the monitoring study will be informed of the results from their home and told how they compare with recommended health guidelines.

I do hope that you will participate in the study. If so please contact me by mail, phone or email to discuss further details and to arrange a monitoring period convenient for you.

Please do not hesitate to contact me if you have any further questions about what is involved.

Yours faithfully,

Arun Sharma
Cranfield University
Tel:
Email:

D.9 Pre-study letter: further information

IEH
Cranfield
Health
Vincent Building
Cranfield
MK43 0AL
Bedfordshire
England
Tel +44 (0) 1234 75
8300
Fax +44 (0) 1234
758380
www.cranfield.ac.uk/health

Date

To Mr X

Cranfield University's study of air quality in your home

Thank you for expressing interest in taking part in our indoor air quality study.

I am writing to provide you with some further details of the monitoring devices and the measurement procedure we use.

A researcher will visit your home at an agreed time and show you the monitoring devices (pictures attached). We will agree suitable locations with you for all the devices that are appropriate for your home. These locations should not cause any inconvenience but the devices should be kept out of reach of any young children. Most of the devices require no attention on your part but we may ask you to turn one type on and off for a fixed period of time.

We will request that you complete a short questionnaire about your home (enclosed), if necessary with the guidance of the researcher. We will also request that you complete an activity diary over the two day monitoring period. This records when certain activities take place such as cooking, the burning of

candles and opening of windows. We would also like you to record the times when you were at home.

The information we collect will be retained on a computer using a code for your house so that it cannot be linked to you on a personal basis. We hope to publish the results of the work in a student thesis and a scientific publication. We will inform you of the results of measurements in your own home.

I will shortly be in contact with you to agree a convenient time and date to visit and begin the monitoring. Enclosed are a consent form and a study information sheet, which you will need to read through and sign; the consent form will be collected at the arranged date.

Please do not hesitate to contact me if you need any further instruction.

Yours faithfully,

Arun Sharma
Cranfield University
Tel:
Email:

D.10 Guide for monitoring procedure & consent form

Cranfield University study of Indoor Air Quality – Guide to use of air quality monitors

Introduction

This guide explains the appropriate positioning and operation of monitors to measure carbon monoxide and other pollutants in air. The aim is to obtain measurements of the amounts of gases and particles in the air that are representative of air breathed by the building occupants. The monitors are quiet, unobtrusive and battery powered or small tubes which require no power.

Monitors are to be set out in the kitchen, main bedroom and the living room for 2 days and are to remain in the decided positions throughout the monitoring period.

Our researcher would like to place the monitors in your home on the arranged date and collect them at an agreed time two days later. Their placement must still allow the safe use of the room for normal occupancy. If there are young children in the household then the selected location should prevent them touching the monitors. Ideal locations for the monitors would be on worktops / tables / shelves etc. that meet (as close as possible) the following criteria:

- About hip- head height off the floor
- About an arm's length from any wall
- Try to place sensors in the middle of the room
- Do not put sensors in direct sunlight and in direct contact with sources of draught, ventilation and pollution
- For the kitchen, place monitors at least 0.5 m but no further than 3 m from the cooker

We also request that you complete the associated forms about your household, your activity diary and use of combustion appliances during the monitoring period.

For further information please contact Arun Sharma on:

Email: **Mobile:**

You may not receive all the equipment described in this guide for your own home; this will depend on characteristics of your home e.g. size and types of appliances.

Thank you for your assistance with this study.

(N.B. The italic writing in brackets will not be included in the copies handed to participants)

ICOM: to monitor carbon monoxide

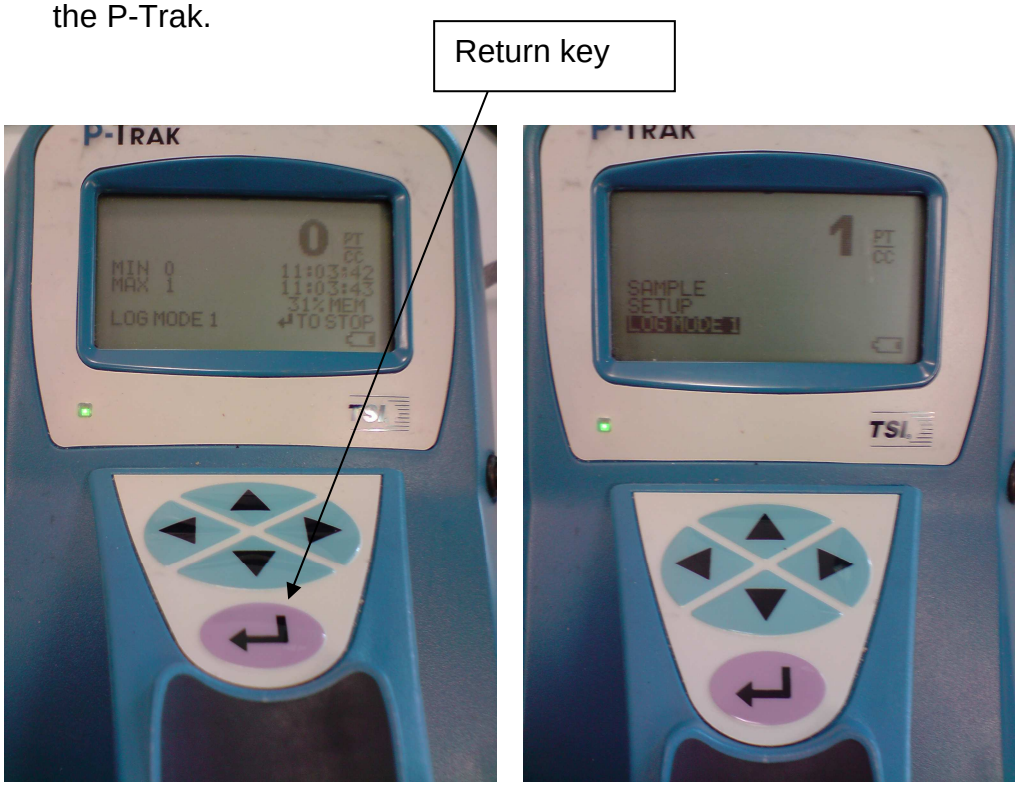
- The researcher will turn on the instrument to begin the monitoring. If for any reason it becomes necessary to turn off, open the panel on the right, as shown above and flip the switch to the “off” position.

EL-USB-CO: to monitor carbon monoxide

- These will be fully set up prior to being provided and can only be turned on and off via a computer at the University with the appropriate software.

P-Trak: to monitor very fine particles *(UFP)*

- If you are requested to turn off the instrument at the end of the logging session, press “return” key (⏎) to stop logging, then turn of the P-Trak.



This screen will appear when logging is in process

The screen that appears after the P-Trak has stopped logging

FirstCheck+ *(monitoring TVOC & CO)*

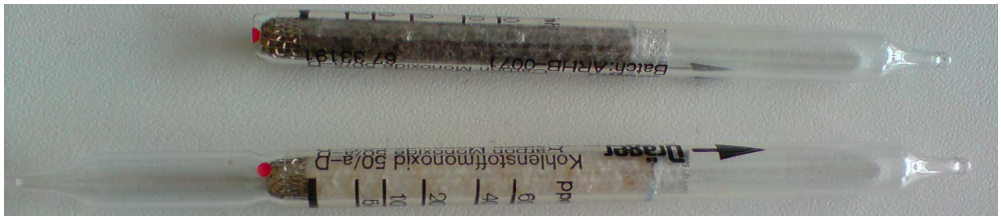
- If you are requested to turn off the instrument after an agreed period of time, press and hold the power button. A bar will then be seen to travel across the bottom of the screen; when it has travelled the length of the screen, release the power button. An egg timer symbol will appear briefly before the logger is completely shut down.

Diffusion Tubes

All these diffusion tubes, when used, will require to be set out for 2 weeks and will need to be posted back to the University using a prepaid and addressed envelope that will be provided. A reminder will be given the day before this is required, such as an email or phone call – depending on your preference.

Type 1: Glass tube in black plastic sleeve *(Drager tubes to monitor CO)*

- These do not require any further assistance after being set out in their locations and are for monitoring carbon monoxide.



The top picture is the Drager tube, which will be placed into the holder shown in the bottom picture

Type 2: – Plastic tube with red cap *(NO_2 tubes)*

- These tubes are for monitoring nitrogen dioxide. To close the tube at the end of the 2 week period you are requested to firmly place the clear/white plastic cap on the open end of the tube. The cap is stored in the prepaid envelope.

This tube on one end has a removable cap which needs to be removed at the start of the monitoring period and placed back on at the end of the monitoring period

Type 3: Metal tubes with screw cap *(VOC tubes)*

- These tubes are for monitoring organic compounds in the air. These will require being capped after the two week period with a screw cap that will be provided.

D.11 Participant information sheet and consent form

Participant:……
Identification Number:……
Title of Project: Indoor air quality in energy efficient homes

Participant Information Sheet

October 2010

Thank you for your interest in this study.

Before you decide whether to take part, we would like you to understand why the research is being conducted and what it would involve for you.

(Part 1 tells you the purpose of this study and what will happen if you take part. Part 2 gives you more detailed information about the conduct of the study).

If, after having read this information sheet, you would like to participate, please sign and return the enclosed consent form. If you have any queries, please contact the researcher – Arun Sharma, mobile:……/ email: a.v.sharma@cranfield.ac.uk

Part 1

1.1 What is the purpose of the study?
The study aims to monitor carbon monoxide and other combustion products in newly built or newly refurbished homes which are built to higher standards of energy efficiency. We wish to investigate whether these higher energy standards could adversely affect the indoor air quality.

1.2 Why have I been chosen?
You have been chosen because your home fits the required criteria.

1.3 Do I have to take part?
No. Furthermore, if you agree to participate, you are free to withdraw at any time without giving any reason.

1.4 Will I receive any payment?
No.

1.5 Will I be informed of the outcomes of my monitoring if I take part?
You will be informed about the carbon monoxide levels and how they compare to recommended air quality guidelines for protection of human health.

Part 2

2.1 What will happen if I do not want to carry on with the study?

If you decide at any time that you no longer wish to carry on, you are free to withdraw at any time without giving any reason.

2.2 What if I have a complaint?

Please contact the project officer, Derrick Crump, at the following address:

2.3 Will my taking part in this study be kept confidential?

Your identity will not be revealed and all data will be stored securely.

2.4 What will happen to the results of the research study?

The information that we will obtain from the monitoring will be used for research purposes where only aggregated statistics will appear in any reports and data will be used in a thesis and possibly further published literature.

2.5 Who is funding the research?

The Gas Safety Trust, a charitable organisation, has provided financial support.

2.6 How long will my involvement in the study last?

We expect the monitoring to last around two weeks. Your participation in completing the associated activity diaries would be for two days and these

would be collected along with the majority of the monitors after two days. Some of the equipment requires a longer time of exposure to obtain results and these would require being posted back (pre-paid postage) to Cranfield University two weeks later.

2.7 Further information and contact details

Arun Sharma,

IEH, Cranfield Health, Vincent Building, Cranfield, Bedfordshire, MK43 0AL.

Mobile Tel: Fax:

Email: a.v.sharma@cranfield.ac.uk

www.cranfield.ac.uk/health

IEH Institute of Environment and Health

Cranfield UNIVERSITY

Participant:……
Identification Number:……
Title of Project: Indoor air quality in energy efficient homes

Monitoring Study Consent Form

Thank you for agreeing to take part in this study. If you have any questions, please ask the researcher before you sign this form. Please tick the following boxes and sign the form to show you have understood and agree the terms of the study.

☐ I confirm that I have read, understood and kept a copy of the "Participant Information Sheet" dated October 2010 for the above study.

☐ I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.

☐ I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without my legal rights being affected.

☐ I understand that my identity will not be revealed and that all data will be stored securely.

☐ I understand that information I provide will only be used for research purposes.

☐ I agree to a researcher placing air quality monitors in my home and to providing some information about the building and occupant activities during the study period.

☐ I agree that monitoring data obtained can be published as part of a research report providing that my identity is not revealed.

I……. (print name)

consent to take part in this study and understand I may withdraw at any time.

Signed……. Date…….

Researcher signed……. Date…….

D.12 Participant activity diary

Please fill in this table by indicating roughly the activities and your whereabouts at the hourly slots by approximately marking the appropriate times

Time	AM 12	1	2	3	4	5	6	7	8	9	10	11	PM 12	1	2	3	4	5	6	7	8	9	10	11
Time spent in:	***Example - if you were in the bedroom from 12 - 7 , 7 - 7:45 in the kitchen, 7:45 - 6 out the house then 6 - 10 spent the majority of the time in the living room and was in another room in the house from 11***																							
Living room																								
Bedroom																								
Kitchen																								
Other																								
Out the house																								
Time spent in:																								
Living room																								
Bedroom																								
Kitchen																								
Other																								
Out the house																								
Periods where all windows were ***shut:***																								
Whole House																								
Living room																								
Bedroom																								
Kitchen (including external door if applicaple)																								
Periods where anyone:																								
Smoked																								
Burned incense																								
Burned candles																								

D.13 Participant cooking activity diary

Name:

Date:

Location of monitors:

Type make of cooker/s:

Approx age of cooker/s:

Time	Record times when used, leave blank if not used			Cooker hood & speed	Comments (for kitchen use and activity only) - internal doors open, trickle ventilators open
	Hobs (State no. if more than 1)	Oven	Grill		
e.g. 13:00 - 14:00	*13:15 on (3) 13:45 (1)*			*13:30 -14:00 - medium*	*trickle ventilators open the whole day*
14:00 - 15:00	*14:05 off*	*14:30 on*	*14:35 - 14:40*		*kitchen door open, lit a candle*
15:00 - 16:00		*15:55 off*		*15:30-15:40 high*	*smoked in the kitchen*
00:00 - 05:00					
05:00 - 06:00					
06:00 - 07:00					
07:00 - 08:00					
08:00 - 09:00					
09:00 - 10:00					
10:00 - 11:00					
11:00 - 12:00					
12:00 - 13:00					
13:00 - 14:00					
14:00 - 15:00					
15:00 - 16:00					
16:00 - 17:00					
17:00 - 18:00					
18:00 - 19:00					
19:00 - 20:00					
20:00 -21:00					
21:00 - 22:00					
22:00 - 23:00					
23:00 - 00:00					

D.14 Housing survey questionnaire

Housing Survey Questionnaire

Name: _____ Address: _____

Date: _____

Section 1 - Basic Property Information

A. Age band
- ☐ Pre 1900
- ☐ 1900 - 1918
- ☐ 1919 - 1944
- ☐ 1945 - 1964
- ☐ 1965 - 1975
- ☐ 1976 - 1980
- ☐ 1981 - 1990
- ☐ 1991 - 1995
- ☐ 1995 - 1997
- ☐ 1998 - 2002
- ☐ Post 2002 - year:.....
- ☐ Don't know

B. Built form
- ☐ House
- ☐ Bungalow
- ☐ Flat
- ☐ Maisonette

o Type
- ☐ Detached
- ☐ Semi-detached
- ☐ Mid terrace
- ☐ End terrace

C. Property location
- ☐ Rural
- ☐ Urban (suburb)
- ☐ Urban (centre)

o Local Traffic & Environment
- ☐ Light traffic
- ☐ Moderate traffic
- ☐ Heavy traffic
- ☐ Industrial area
- ☐ Heavy industry
- ☐ Chemical industry
- ☐ Small-scale industry

D. How many levels does your property have?

:.....

o If a Flat, what floor are you on?

:.....

E. Number of rooms

Kitchen:.....

Bedroom:.....

Living room:.....

Utility room:.....

Basement:.....

Conservatory:.....

WC / Bathroom:.....

Other:.....

F. Do you have an attached or integral garage?
- ☐ Yes - attached
- ☐ Yes - integral
- ☐ No

o If yes, do you use it to store a car or motorbike?
- ☐ Yes
- ☐ No

Section 2 - Existing Home Insulation

A. Main glazing type
- ☐ Single
- ☐ Double
- ☐ Mixed

o Main glazing frame
- ☐ Wood
- ☐ Plastic
- ☐ Metal

o Do your windows have trickle ventilators?
- ☐ Yes - all
- ☐ Yes - some
- ☐ No
- ☐ Don't know

B. Wall type
- ☐ Solid
- ☐ Cavity
- ☐ Timber-frame
- ☐ Don't know
- ☐ Other:.....

o Cavity wall insulation
- ☐ Insulated
- ☐ Un-insulated
- ☐ Don't Know
- ☐ Not applicable

C. Ground Level Floor type(s) - tick all that apply
- ☐ Solid floor
- ☐ Suspended timber floor
- ☐ Suspended chipboard floor
- ☐ Concrete beams / blocks
- ☐ Don't know
- ☐ Other:.....

o Ground Level floor insulation
- ☐ Insulated - all
- ☐ Insulated - some
- ☐ Un-insulated
- ☐ Don't know

Section 3 - Heating and Cooking

A. Main heating

- ☐ Central heating system
- ☐ Individual radiators
- ☐ Underfloor
- ☐ Single stoves
- ☐ Open fireplace
- ☐ Other:.....

  - Main heating fuel

- ☐ Oil
- ☐ Gas
- ☐ Coal
- ☐ Wood
- ☐ Electric
- ☐ Biomass
- ☐ Other:.....

Room or location of heating source:.....

Make & age of appliance:.....

  - Does your main heating have a flue/chimney?

- ☐ Yes
- ☐ No
- ☐ Not Applicable

B. Secondary heating

- ☐ Individual radiators
- ☐ Underfloor
- ☐ Single stoves
- ☐ Open fireplace
- ☐ Other:.....

  - Secondary heating fuel

- ☐ Oil
- ☐ Gas
- ☐ Coal
- ☐ Wood
- ☐ Electric
- ☐ Biomass
- ☐ Other:.....

Room or location of heating source:.....

Make & age of appliance:.....

  - Does your secondary heating have a flue/chimney?

- ☐ Yes
- ☐ No
- ☐ Not Applicable

C. Indicate the current heating patterns by the number of hours during each time period:

Space heating

- ☐ Not applicable

6am - 12 noon:.....

12 noon - 6pm:.....

6pm - 12 midnight:.....

12 midnight - 6am:.....

  - Water heating (if scheduled)

- ☐ Not applicable

6am - 12 noon:.....

12 noon - 6pm:.....

6pm - 12 midnight:.....

12 midnight - 6am:.....

Please indicate the make and age of your boiler for water heating if applicable:.....
.....

D. Primary Cooking fuel -

- ☐ Natural gas
- ☐ Electricity
- ☐ Oil
- ☐ Solid Fuel
- ☐ Bottled gas
- ☐ Biomass
- ☐ Other:.....
- ☐ Not applicable

Please indicate type of appliance e.g. cooker, hobs

:.....

E. Secondary Cooking fuel -

- ☐ Natural gas
- ☐ Electricity
- ☐ Oil
- ☐ Solid Fuel
- ☐ Bottled gas
- ☐ Biomass
- ☐ Other:.....
- ☐ Not applicable

Please indicate type of appliance e.g. oven, grill

:.....

F. Cooker hood

- ☐ Yes
- ☐ No

  - If yes, what is your cooker hood type?

- ☐ Extract to outside
- ☐ Re-circulates through filter

  - Does your Cooker have a pilot light?

- ☐ Yes
- ☐ No
- ☐ Don't know

Section 4 - Occupant Information

A. Number of occupants - Please indicate how many for each age group applicable:

65+ years:.....

17 - 65 years:.....

5 -16 years:.....

0 -5 years:.....

B. Does anyone smoke a pipe or cigarettes indoors regularly?

- ☐ Yes
- ☐ No

  - If yes, approximately how many per day?

:..... day

C. Does anyone burn incense or candles indoors regularly?

- ☐ Yes
- ☐ No

  - If yes, approximately how many times a week?

Candles:.....week

Incense:.....week

D.15 Housing Survey Questionnaire – guidance sheet

The following notes are to provide guidance in filling in the questionnaire on the property type.

Section 1 - Basic Property Information

A. Indicate the age band of when the property was built if known. If your property was built after 2002, please indicate year it was built if known.
B. Tick the boxes that describe the type of building.
C. Select from the list which option best describes the local area and mark as many boxes as applicable concerning traffic on the road/s immediately adjacent to the property and industry in the local area.
D. Indicate how many floors the property has e.g. if house with a ground floor and upstairs on one level write '2'. If the property is a flat, write what floor you are situated on, i.e. ground / 1st etc.
E. Write the number of rooms of each type listed and add the number of any other rooms not listed.
F. Indicate if your property has an attached or integral garage. Attached means it shares a wall with the main property. Integral means there is a room above that is part of the property.

Section 2 – Existing Home Insulation

A. Mark what type of glazing the windows are and the material of the frame for the windows. Also indicate if your windows have trickle ventilators (trickle ventilators are usually incorporated within the frame at the top of a window and are controllable flaps that can be opened or closed to allow some outside air in without the window being opened).
B. Specify the type of structure of the outside walls. If it is a cavity wall construction identify whether the cavity is insulated (e.g. with blown in mineral fibre).
C. Indicate the type of floor construction of the ground floor (excluding basements/cellars). If a flat refer to your own floor and if a maisonette the lower level floor.

Section 3 – Heating and Cooking

A. Indicate the main type of heating used in the home and the fuel type for this heating. Please provide location of appliance e.g. gas boiler in kitchen and any details of manufacturer and age (approximate number of years). Please indicate if his appliance has a flue/chimney.
B. The same as A. above, but for a secondary heating of the property if applicable e.g. a wood burning stove or an electric fire.
C. Write the number of hours for each time period identified that space heating and water heating is used at this time of year. For example, if a current schedule for the central heating was on a timer and would come on at half past 6 in the morning for 2 hours, then you would write two hours in the 6 am – 12 noon space of the space heating section.
D. Tick the box for what primary cooking fuel you use and what appliances this is fuel for, for example if you had a gas hob, gas oven and gas grill, tick the natural gas box and list these appliances (make and model) in the space provided.
E. Same as D. above but for a secondary fuel of cooking e.g. may be electric oven whereas gas hob recorded as primary cooking fuel.
F. Indicate if your kitchen has a cooker hood or extractor fan fitted and where the air is ventilated to; if outside there will be a duct and an outlet on the outside wall. Also please record if you have a pilot light that is constantly burning.

Section 4 – Occupant Information

A. Write how many people live in the property by filling in the age groups, for example if one 35 year old and a 10 year old lived in the house write 1 in the 17 - 65 section and 1 in the 5 -16 section and leave the rest blank.
B. Indicate if anyone in the household smokes and approximately how many products are smoked between all the smokers living in the house by writing an estimated number per day.
C. Record typical use of candles and incense as number of periods these are burnt per week e.g. lit once per week.

D.16 Diffusive tubes monitoring form

Identification Number:……..

Tubes are to be closed on:

If you are not able to close them on the exact date this is not a problem, just do it as near to the date as possible and record on the chart the approximate time and the date, (it is better to be a day or two late rather than early).

Plastic Tubes and Glass tubes monitoring form

Tube type	Tube No.	Location	Opened		Closed	
			Date	Time	Date	Time
Plastic - capped						
Plastic - capped						
Plastic - capped						
Glass						
Glass						
Glass						

To close the plastic tubes, please use the white caps which are kept in the jiffy bag and ensure that they are placed on tightly. To seal the glass tubes, please use a piece of Blu-Tack provided. Please try to ensure that all tubes are sealed tightly so that air cannot enter. Place all tubes and this completed sheet in the jiffy bag and mail it back to Cranfield University (postage pre-paid).

Thank you for your time and assistance.

D.17 Post-study letter: scenario one

IEH
Cranfield Health
Vincent Building
Cranfield
MK43 0AL
Bedfordshire
England
Tel +44 (0) 1234 75 8300
Fax +44 (0) 1234 758380
www.cranfield.ac.uk/health

Example letter to participant

Date

Cranfield University's study of air quality in your home

Thank you for taking part in this study and for the successful return of the monitoring equipment.

I am writing to inform you that the results of the monitoring study in your home have shown that the levels of carbon monoxide/nitrogen dioxide are low and within the World Health Organisation guidelines for the protection of human health.

If you wish to know your results in further detail please contact me.

Yours faithfully,

Arun Sharma
Cranfield University
Tel:
email:

Certificate No EMS 98287 ISO 14001
The Gas Safety Trust – Proud funders of this programme
The Queen's Anniversary Prizes 2005

D.18 Post-study letter: scenario two

IEH
Cranfield Health
Vincent Building
Cranfield
MK43 0AL
Bedfordshire
England
Tel +44 (0) 1234 75 8300
Fax +44 (0) 1234 758380
www.cranfield.ac.uk/health

Template to be adjusted on a case by case basis *Example letter to participant – exact wording will vary depending upon the monitoring outcome*

Date

Cranfield University's study of air quality in your home

Thank you for taking part in this study and for the successful return of the monitoring equipment. I am writing to inform you that the results of the monitoring study in your home have shown that the carbon monoxide and/or nitrogen dioxide exceed the recommended World Health Organisation guideline levels for the protection of human health.

We recommend that you obtain the services of a registered and qualified gas engineer to check your combustion (heating/cooking) appliances to ensure that the fumes being released are not a risk to the health of occupants. It is recommended by the Gas Safe Register that gas appliances are safety checked at least once every year, and more frequently if recommended by manufacturer's guidelines.

I attach a summary of the results found which you may wish to discuss with the engineer.

Yours faithfully,

Arun Sharma

Cranfield University
Tel:
email:

D.19 Post-study information: scenario three

If the occupational exposure limits for CO (see Table D-1 below) are exceeded in any home the participant will be contacted immediately via telephone and by letter. The participant will be advised that the concentrations are higher than those recommended to protect the health of healthy adults in the workplace. It will be strongly recommend that they do not use their gas appliances and should contact a registered gas engineer to arrange for the appliances to be checked without delay. We will also explain that we could provide the results of the monitoring to the engineer to inform their investigation.

Figure D-1: CO Guidelines for comparison to monitored study homes

Type of guideline	CO concentration and averaging period
Occupation exposure limit	30 ppm - 8 hour 200 ppm - 15 min
WHO	87 ppm - 15 minutes 52 ppm - 30 minutes 26 ppm - 1 hour 9 ppm - 8 hours 6 ppm – 24 hours

Appendix E Further pollutant data from monitoring during the main study

E.1 MK2

The monitoring was for approximately 1.5 days, all windows and doors for ventilation were shut except for a 1 hour period when the bedroom window was reported to be open very briefly whilst cooking. This home had constant mechanical ventilation, extracting air from the home and replacing with fresh outside air, which can be solar preheated. The gas hobs were reported to have been used on four different occasions during the monitoring period.

E.1.1 Carbon monoxide

From the activity diary, it is observed that when the hobs are used CO is produced which coincides with the maximum values observed and other peaks. The living room has elevated levels around the same time as the kitchen when reported gas cooking activity occurs, but the level monitored in the living room was not as high as that in the kitchen. Apart from the use of the hobs, there was no other reported activity which may have caused elevated CO. During every cooking activity the cooker hood was used. A summary of the data recorded in MK2 is given in Table E-1.

Table E-1: CO data from MK2

	Kitchen 1	Kitchen 2	Living room	Bedroom
Maximum	10.7 ppm	6.8 ppm	2.5 ppm	1.0 ppm
Minimum	0.2 ppm	0.0 ppm	0.0 ppm	0.2 ppm
Average	0.7 ppm	0.1 ppm	0.1 ppm	0.4 ppm
Standard deviation	0.8 ppm	0.5 ppm	0.3 ppm	0.2 ppm

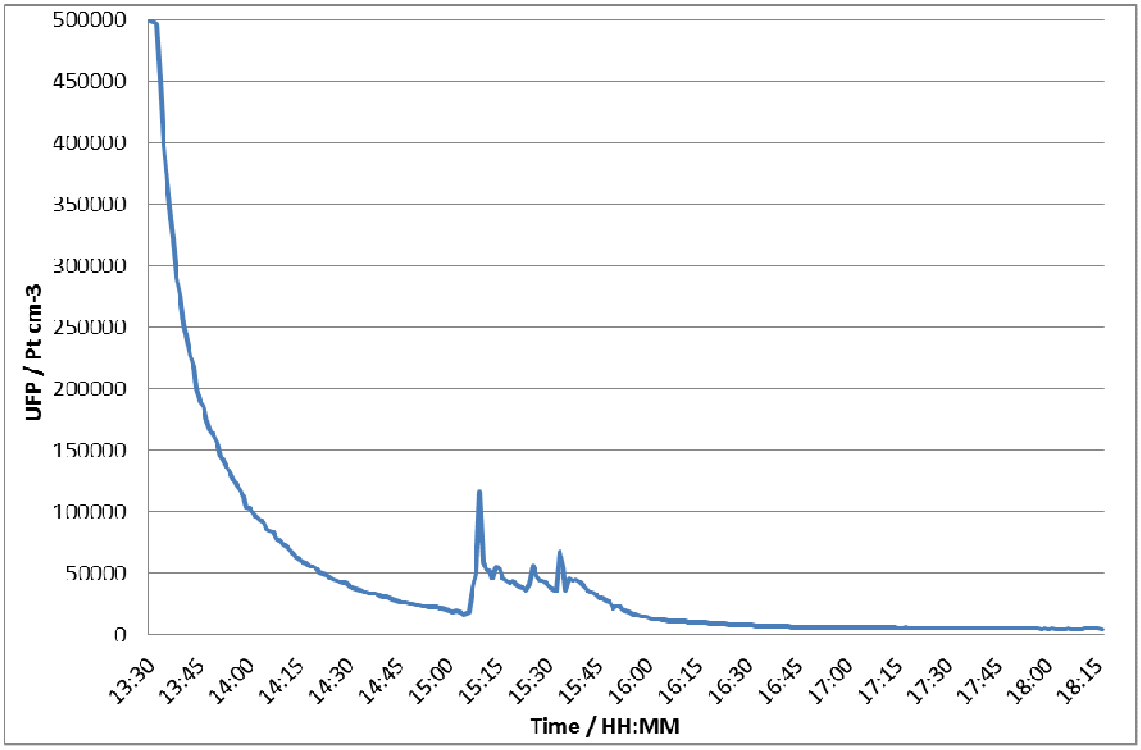
E.1.2 Ultrafine particles

The UPC was located adjacent to the hob, when the monitors were being set out, the participants had just finished preparing lunch using the gas hobs to fry, which may be an explanation for the highly elevated UFP count as seen in Table E-2. The maximum of 500,000 pt cm^{-3} was observed (which is the maximum range to which the monitor records), at the beginning of the monitoring and a steady decrease thereafter was observed, which is better depicted in Figure E-1. The UPC ran for approximately 5 hours in the kitchen during which no other activities were reported. A summary of the recorded UFP levels can be found in Table E-2.

Table E-2: Summary of UFP in MK2

	UFP (pt cm^{-3})
Maximum	500,000
Minimum	4,733
Average	46,103
Standard Deviation	80,863

Figure E-1: UFP data recorded in MK2



E.1.3 Nitrogen dioxide

The NO_2 tubes were exposed for 20 days (Table E-3). A tube was also set out in the living room but was lost in the property.

Table E-3: Average NO_2 levels over 20 day's exposure in MK2

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	486	11.2
Bedroom	486	5.3

E.2 MK3

The monitoring was for approximately 2 days and for both days all windows and doors for ventilation were shut. The householder noted that the trickle ventilators were opened throughout the monitoring. MK3 has the same mechanical ventilation system as MK2 which is constantly running throughout the day. The gas hobs were reported to have been used three times during the

monitoring and the gas central heating was timed to come on for 9 hours a day. The kitchen and living room are of open plan design.

E.2.1 Carbon monoxide

One of the two monitors in the kitchen was placed in the middle of the kitchen on a table with the other monitor adjacent to the gas hobs. The CO monitor in the bedroom did not log any data other than 0 ppm and its data is not shown in the Table E-4. The peaks observed in this house were due to use of the gas hobs, but the levels did not elevate higher than 3 ppm on any CO monitor and the peak occurred when two hobs were reported to be used for 45 minutes. From the activity diary, it is observed that when the hobs are used CO is produced which coincides to the maximum values observed and other peaks. The living room show elevated levels around the same time as the kitchens when reported gas cooking activity occurs, but the level monitored in the living room was not as high as that in the kitchen. Apart from the use of the hobs, there was no other reported activities which may of caused elevated CO. During every cooking activity the cooker hood was used. A summary of the data recorded in MK2 is given in Table E-4.

Table E-4: CO data from MK3

	Kitchen 1	Kitchen 2	Living room
Maximum	1.7 ppm	2.7 ppm	1.2 ppm
Minimum	0.2 ppm	0.0 ppm	0.1 ppm
Average	0.5 ppm	0.1 ppm	0.4 ppm
Standard deviation	0.2 ppm	0.2 ppm	0.2 ppm

E.2.2 Nitrogen dioxide

The NO_2 tubes were exposed for 21 days (Table E-5).

Table E-5: Average NO_2 levels over 21 day's exposure in MK3

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	493	17.1
Living room	493	15.1
Bedroom	493	8.9

E.3 MK4

MK4 was monitored on two occasions during the heating season for approximately 1.5 days on both occasions. During the first monitoring period, the mechanical ventilation was awaiting repair, the extract feature was functioning but the circulation of outside air was not. The air inside MK4 upon entering the home at monitoring period 1 was stale and there was a distinct difference in the perception of the quality of air compared to the second monitoring period. The mechanical ventilation in MK4 is the same to that in MK2 and MK3. Monitors were set out in the same locations during both monitoring periods. This property had an open plan kitchen and living room. The participant noted that and gas central heating was on all day and set to 18 ℃ on the thermostat. In both monitoring periods trickle ventilators were opened.

E.3.1 Carbon monoxide

A summary of the CO data recorded in MK4 in both monitoring periods is given in Table E-6. The maximum during monitoring period one was obtained in a brief period of the use of a gas hob where the cooker hood was also used. Other cooking occurred in monitoring period 1 on the second day of monitoring and the CO did not exceed 1.6 ppm. The maximum in monitoring period 2 occurred when no reported activity was recorded on the second day of monitoring. There was no reported use of kitchen cooking appliances on day 2 and on only one occasion on the first day, which correlated with slightly elevated CO levels.

Table E-6: CO data from MK4 from monitoring period 1 (P1) and monitoring period 2 (P2)

	Kitchen 1		Kitchen 2		Living room		Bedroom	
	P1	P2	P1	P2	P1	P2	P1	P2
Maximum (ppm)	4.8	2.0	-	0.5	1.1	0.5	-	1.2
Minimum (ppm)	0.2	1.1	-	0.0	0.0	0.0	-	0.7
Average (ppm)	0.5	1.3	-	0.0	0.0	0.1	-	0.8
Standard deviation (ppm)	0.3	0.1	-	0.0	0.0	0.2	-	0.1

E.3.2 Ultrafine particles

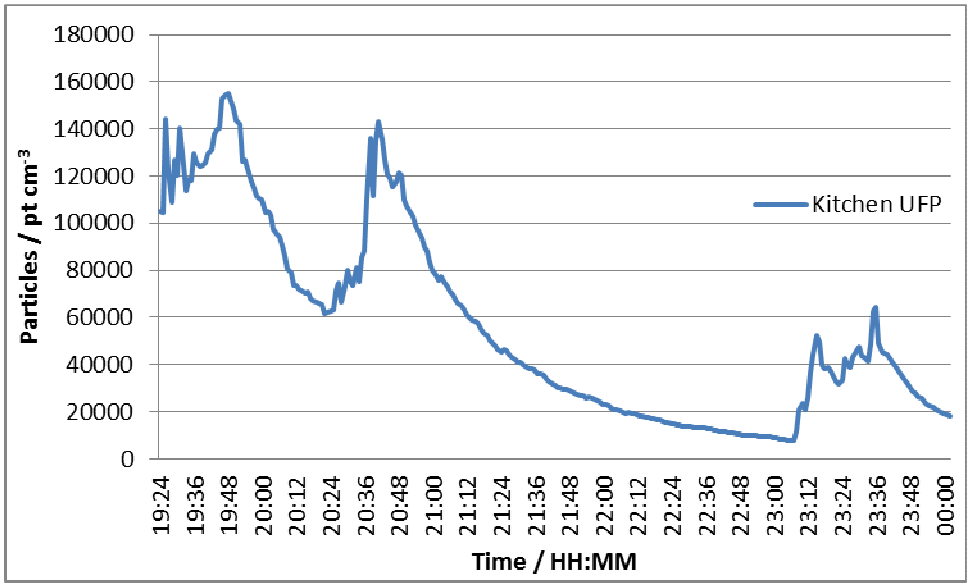
The UPC did not record any data for the first monitoring period. On the second monitoring period the electric oven was on for 1.75 h with the kitchen window open during this time. The UPC ran for approximately 4.5 hours in the kitchen during which no other activities were reported other than the baking during the monitor's operation. A summary of the recorded UFP levels is given in Table E-7.

Table E-7: Summary of UFP in MK4 – monitoring period 2

	UFP (pt cm^{-3})
Maximum	154,900
Minimum	7,530
Average	56,382
Standard Deviation	41,534

The elevated levels can be seen in Figure E-2. Cooking was reported from 19:00 – 20:45, with a decline in UFP observed around 19:50 for around 20 minutes, which may be due to the window being opened. Around the time when the oven is turned off the levels decline to levels lower than observed during the cooking period.

Figure E-2: UFP in MK4 – monitoring period 2



E.3.3 Nitrogen dioxide

The NO_2 tubes were exposed for 14 days in both monitoring periods (Table E-8).

Table E-8: Average NO_2 levels over 14 days in MK4 for P1 and P2

Tube location	Length of exposure (hours)		Average NO_2 (µg m^{-3})	
	P1	P2	P1	P2
Kitchen	336	340	11.9	14.4
Living room	336	340	11.8	13.4
Bedroom	336	340	8.5	13.4

E.4 MK5

The monitoring was for approximately 2 days. During the monitoring period, the electric cooking appliances were reported to have been used four times.

E.4.1 Carbon monoxide

No reported use of kitchen appliances or the gas central heating coincided with the maximum CO observed in this property, Table E-9 shows the CO data recorded in MK5.

Table E-9: CO data from MK5

	Kitchen 1	Kitchen 2	Living room	Bedroom
Maximum	1.6 ppm	0.8 ppm	1.5 ppm	1.5 ppm
Minimum	0.3 ppm	0.0 ppm	0.4 ppm	0.0ppm
Average	0.9 ppm	0.0 ppm	1.0 ppm	0.5 ppm
Standard deviation	0.2 ppm	0.1 ppm	0.3 ppm	0.3 ppm

E.4.2 Ultrafine particles

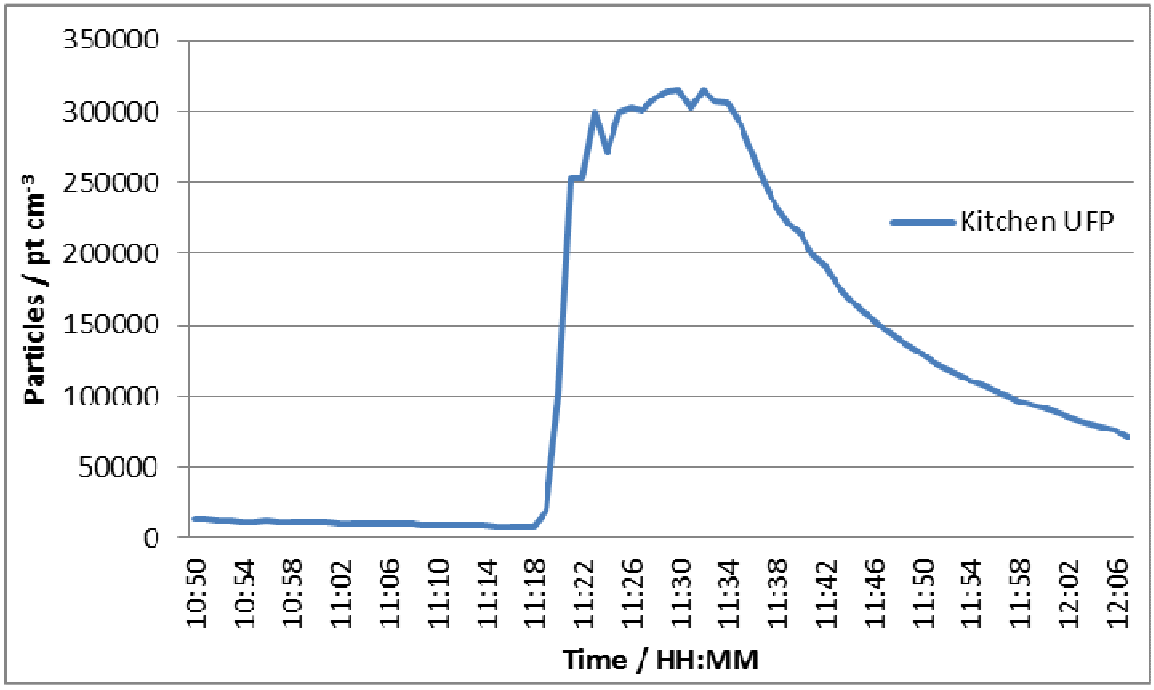
A summary of the UFP observed in an 80 minute period in which the UPC operated can be found in Table E-10. The maximum of over 300,000 pt cm^{-3} coincided with the use of the electric hob, when also the use of an electric toaster and kettle had been reported around the same period. The minimum was only reached briefly prior to the cooking period, levels were dropping until this activity caused the increase.

Table E-10: Summary of UFP in MK5

	UFP (pt cm^{-3})
Maximum	315,683
Minimum	8,575
Average	119,075
Standard Deviation	110,122

The changes in UFP concentration can be observed in Figure E-3, where a sharp rise is observed approximately 10 minutes after reported use of electric cooking appliances. The appliances were used for 15 minutes, levels still increased for approximately 5 minutes after the appliances had stopped being used, and then decline, but at a less steep rate than the initial incline.

Figure E-3: UFP in MK5



E.4.3 Nitrogen dioxide

The NO_2 tubes were exposed for 14 days (Table E-11).

Table E-11: Average NO_2 levels over 14 day's exposure in MK5

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	344	12.0
Living room	344	9.8
Bedroom	344	10.9

E.5 MK6

The monitoring was for approximately 1.5 days. The kitchen and living room were of open plan design. The communal lighting for the flat was provided by photovoltaic panels on the roof. The property also had mechanical ventilation which had ducts throughout and can be switched on manually by the occupant. During the monitoring period, the occupant did not record any cooking or kitchen activities. As the monitors were being set out, the occupants had finished cooking. In the basement of the property is a parking garage. The gas central heating was on a timer to come on for 1 hour in the morning, 1 hour in the afternoon and 1 hour in the evening and also to heat water for an hour in the morning and an hour in the afternoon.

E.5.1 Carbon monoxide

From the activity diary no cooking activities occurred during the time the diaries were kept. CO levels peaked at 3.3 ppm in the kitchen and 2.2 ppm in the open-plan living room. A summary of the data recorded in MK6 is given in Table E-12.

Table E-12: CO data from MK6

	Kitchen 1	Kitchen 2	Living room	Bedroom
Maximum	1.9 ppm	3.3 ppm	2.2 ppm	0.8 ppm
Minimum	1.2 ppm	0.3 ppm	1.5 ppm	0.0 ppm
Average	1.5 ppm	1.2 ppm	1.8 ppm	0.0 ppm
Standard deviation	0.1 ppm	0.3 ppm	0.1 ppm	0.1 ppm

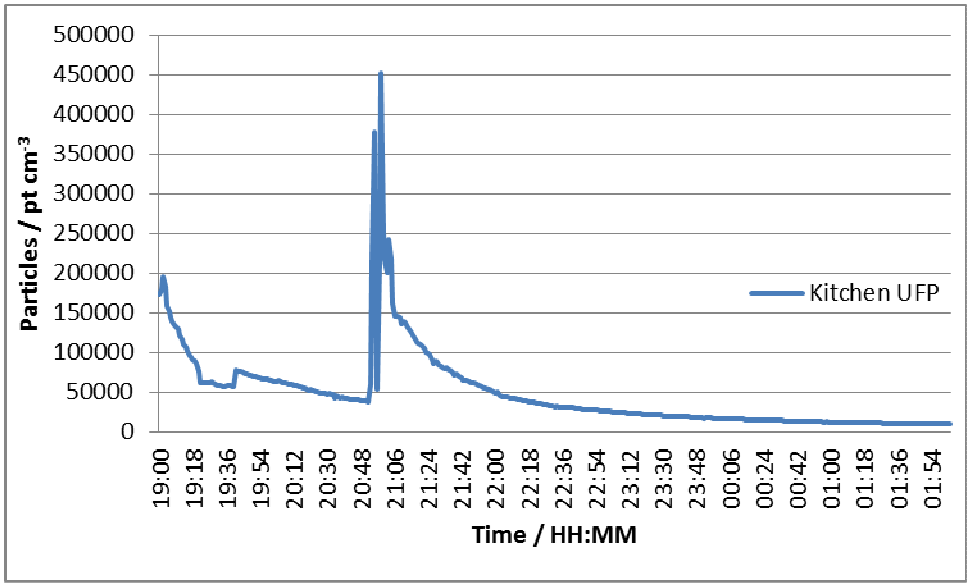
E.5.2 Ultrafine particles and total volatile organic compounds

When the monitors were being set out, the participants had just finished preparing dinner, initial UFP levels monitored were elevated compared to those expected as background levels. These levels fell steadily, the maximum was observed about two hours into the monitoring, but no combustion or other activities were reported coinciding with this peak (Figure E-4). The UPC ran for approximately 7 hours and the PID ran for 8 hours and the data from this time is also summarised in Table E-13. No activity was reported during the operation of the PID or UPC.

Table E-13: Summary of UFPs and TVOCs in MK6

	UFP (pt cm^{-3})	TVOC (µg m^{-3})
Maximum	451,765	1,631
Minimum	9,030	0
Average	48,026	386
Standard Deviation	49,870	440

Figure E-4: UFP in MK6



E.5.3 Nitrogen dioxide

The NO_2 tubes were exposed for 14 days (Table E-14).

Table E-14: Average NO_2 levels over 14 day's exposure in MK6

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	336	12.2
Living room	336	13.1
Bedroom	336	7.9

E.6 MK7

The monitoring was for approximately 3.5 days, as the monitors could not be collected after the 2 days. The participant volunteered to fill in extra activity diaries for the extra two dates. Two of the four activity diaries had no cooking activity reported. Two cooking activities were reported during the monitoring period, neither involved use of the gas hobs. The gas central heating was set to come on for 2 hours in the morning and 2 hours in the evening, as was the water heating which was the same combi-boiler.

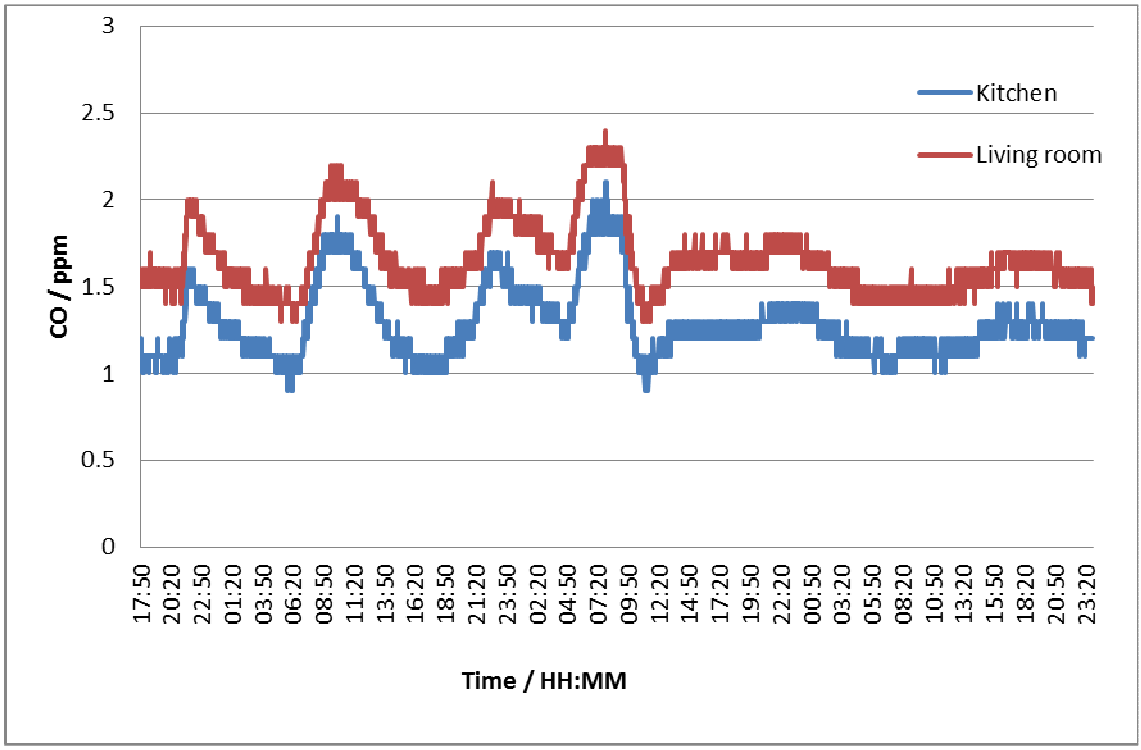
E.6.1 Carbon monoxide

A summary of the data recorded in MK7 is given in Table E-15, one of the CO monitors did not record any data and therefore is not included in the results. The peaks observed were during the morning, where the level was elevated above the averages. This may be due to the heating, as it also rises in the evening. This trend can be observed in Figure E-5, with both rooms having the same trends as one another, which may be expected with the open plan design of the kitchen and living room.

Table E-15: CO data from MK7

	Kitchen	Living room	Bedroom
Maximum	2.1 ppm	2.4 ppm	1.5 ppm
Minimum	0.9 ppm	1.3 ppm	0.0 ppm
Average	1.3 ppm	1.7 ppm	0.2 ppm
Standard deviation	0.2 ppm	0.2 ppm	0.4 ppm

Figure E-5: CO pattern over the monitoring period in the kitchen and living room of MK7



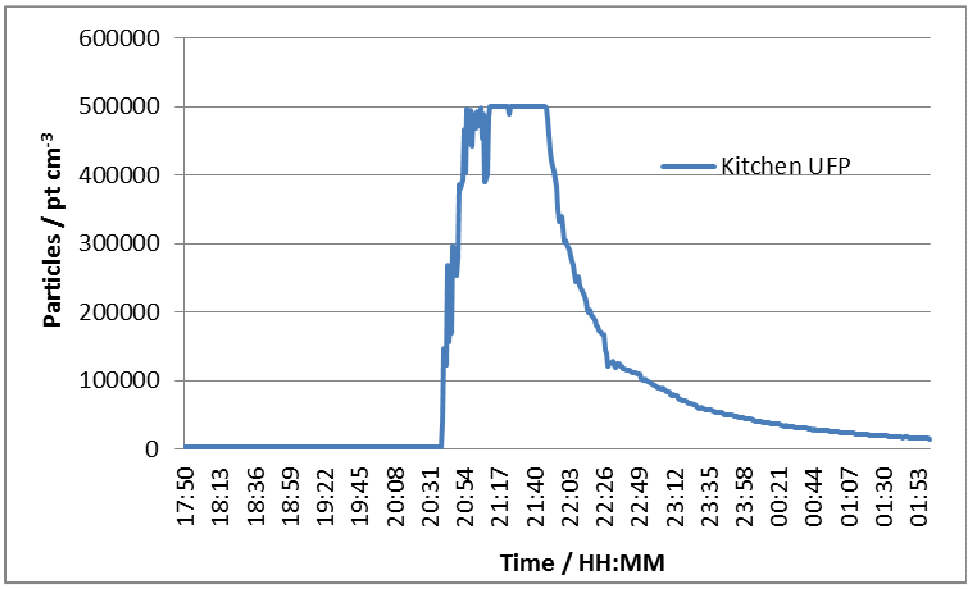
E.6.2 Ultrafine particles and total volatile organic compounds

Table E-16 summarises the UFP monitored over 8 hours and the PID monitored over 4 hours. The UPCs maximum range of 500,000 pt cm^{-3} was observed during its operation, which coincides with the use of the electric oven which was on for a period of an hour. A bell shaped curve was observed during the cooking period which began to decrease approximately 20 minutes later (Figure E-6). This delay in the measured decrease is probably because 500,000 pt cm^{-3} is the maximum that can be monitored on the UPC and the number may be decreasing when still above the range, but is observed as a plateau in Figure E-6. For the PID, there was no reported activity when the maximum was observed. While the UFP levels are elevated and above the maximum reading of the machine, the TVOC levels were also elevated compared to the average.

Table E-16: Summary of UFPs and TVOCs in MK7

	UFP (pt cm^{-3})	TVOC (µg m^{-3})
Maximum	500,000	2,799
Minimum	1,919	0
Average	105,417	253
Standard Deviation	160,104	392

Figure E-6: UFP levels in the kitchen of MK7



E.6.3 Nitrogen dioxide

The NO_2 tubes were exposed for 19 days (Table E-17).

Table E-17: Average NO_2 levels over 19 day's exposure in MK7

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	446	9.2
Living room	446	7.1
Bedroom	446	6.1

E.7 MK8

Monitoring was conducted for approximately 1.5 days. On three different occasions gas cooking activities were reported, one of which the cooker hood was used. The majority of the occupant's time was spent in the living room, which was of open-plan design with the kitchen.

E.7.1 Carbon monoxide

In comparison to some of the other homes where gas cooking had occurred, MK8 does not have a large CO maximum, the highest observed was 3.6 ppm in the living room about 20 minutes after cooking had been reported. A summary of the data recorded in MK8 is given in Table E-18.

Table E-18: CO data from MK8

	Kitchen 1	Kitchen 2	Living room	Bedroom
Maximum	2.6 ppm	2.0 ppm	3.6 ppm	0.0 ppm
Minimum	1.1 ppm	0.0 ppm	1.9 ppm	0.0 ppm
Average	1.5 ppm	0.0 ppm	2.5 ppm	0.0 ppm
Standard deviation	0.3 ppm	0.1 ppm	0.4 ppm	0.0 ppm

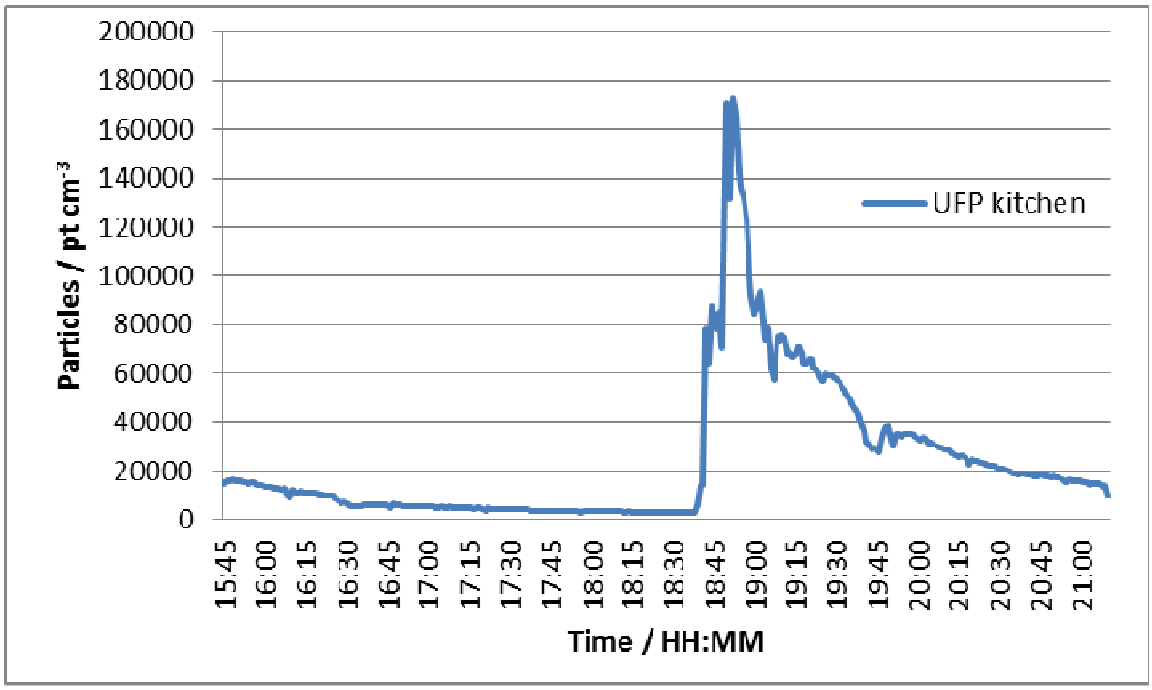
E.7.2 Ultrafine particles and total volatile organic compounds

Table E-19 summarises the UFPs monitored over a 5 hour period and the PID over an 8 hour period. The maximum UFP count occurred during a period where the gas hobs were active over 40 minutes, the only period where the UFP count exceeded 100,000 pt cm^{-3}. Figure E-7 shows this steep increase and the slower decrease. There is no reported activity when the maximum occurred for the PID. During the cooking activity where the UFP maximum occurred TVOC levels are not very different to the average level monitored.

Table E-19: Summary of UFPs and TVOCs in MK8

	UFP (pt cm^{-3})	TVOC (µg m^{-3})
Maximum	172,833	2,420
Minimum	2,820	0
Average	24,359	549
Standard Deviation	30,356	508

Figure E-7: UFP levels in the kitchen of MK7



E.7.3 Nitrogen dioxide

The NO_2 tubes were exposed for 14 days (Table E-20).

Table E-20: Average NO_2 levels over 14 day's exposure in MK8

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	330	5.9
Living room	330	6.1
Bedroom	330	6.1

E.8 MK9

Monitoring was conducted for approximately 1.5 days. On two different occasions cooking activities were reported. This home had no gas cooking appliances. The occupant reported spending the majority of their time in the living room, which was of open plan-design with the kitchen.

E.8.1 Carbon monoxide

MK9 did not have a large CO maximum. This property does not have any gas cooking appliances and the gas central heating system boiler is not located within the flat. The highest observed CO concentration was monitored in the bedroom. A summary of the data recorded in MK9 is given in Table E-21.

Table E-21: CO data from MK9

	Kitchen	Bedroom
Maximum	1.3 ppm	1.8 ppm
Minimum	0.6 ppm	1.2 ppm
Average	0.8 ppm	1.4 ppm
Standard deviation	0.2 ppm	0.2 ppm

E.8.2 Ultrafine particles and total volatile organic compounds

Table E-22 summarises the UFP monitored over a 6 hour period and the PID over 2 hours. The maximum occurred at the start of the monitoring period and steadily declined over the 6 hours of operation. It was reported that a cooking activity with the electric cooker had occurred prior to monitoring, and there was no reported activity during the operation of the UPC and PID.

Table E-22: Summary of UFPs and TVOCs in MK9

	UFP (pt cm^{-3})	TVOC (µg m^{-3})
Maximum	43,135	12,331
Minimum	3,284	240
Average	13,516	2,134
Standard Deviation	10,392	1,828

E.8.3 Nitrogen dioxide

The NO_2 tubes were exposed for 19 days (Table E-23).

Table E-23: Average NO_2 levels over 19 day's exposure in MK9

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	459	3.4
Living room	459	2.6
Bedroom	459	3.2

E.9 CH1

CH1 was also monitored as part of the pilot studies prior to the heating season (Appendix C, H5). The heating was set on a timer to come on for an hour in the morning and two hours in the evening. From the activity diary, there were only

two instances where any cooking activity was recorded. This was for a 20 minute period on the first day with two hobs used and 15 minute period where two gas hobs were used on the second day. The monitoring was for approximately 1.5 days. The participant filled in the cooking activity diary on both days but did not fill in the other activity diary detailing time spend around the house and the ventilation pattern for one day.

E.9.1 Carbon monoxide

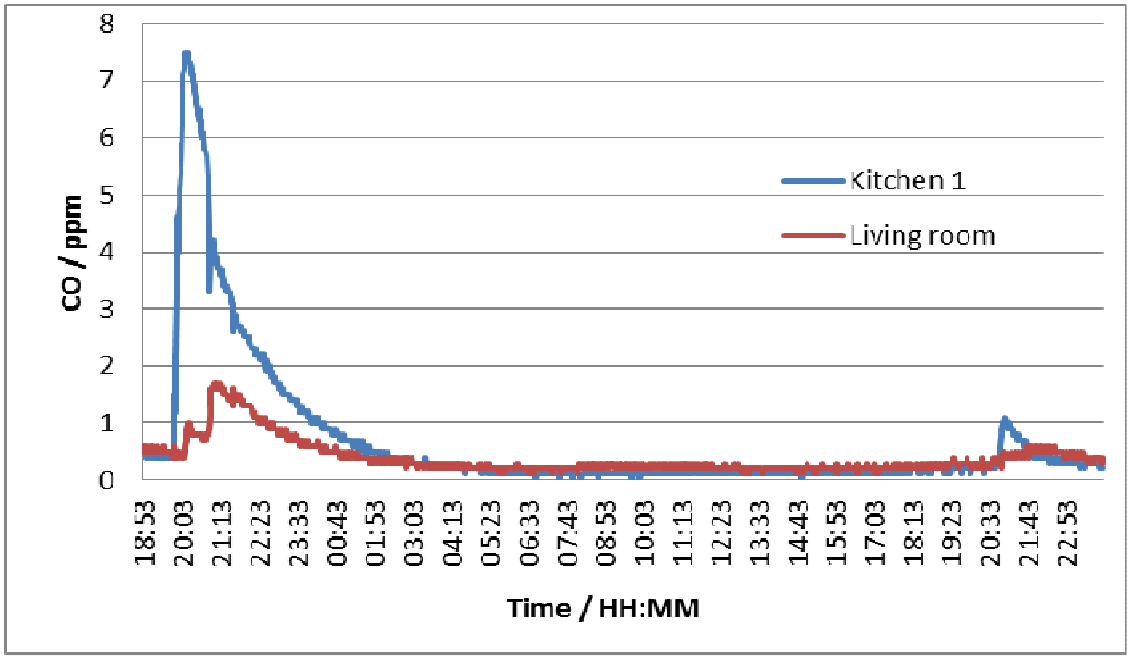
A Drager diffusive tube was set out in the bedroom for 18 days and the reading was taken as 60 ppm h^{-1}, equating to an average of 0.1 ppm over the exposure period. The data is summarised in Table E-24.

Table E-24: CO data from CH1

	Kitchen 1	Kitchen 2	Kitchen 3	Living room
Maximum	7.5 ppm	7.0 ppm	10.0 ppm	1.7 ppm
Minimum	0.0 ppm	0.0 ppm	0.0 ppm	0.1 ppm
Average	0.7 ppm	0.2 ppm	0.4 ppm	0.4 ppm
Standard deviation	1.3 ppm	1.0 ppm	1.4 ppm	0.3 ppm

From the activity diary, it is observed that on the first day when the hobs are used CO is produced which coincides to the maximum values observed. On the second day when the 2 hobs were reported to have been used, there was no large change in the levels of CO recorded, and the maximum CO monitored peaked very briefly at 1.1 ppm. Apart from the use of the hobs, there was no other reported activity which may have caused elevated CO and the CO does not deviate from the background levels. These peaks and the trends of CO can be observed in Figure E-8.

Figure E-8: CO trend for Kitchen 1 and the living room monitor in CH1



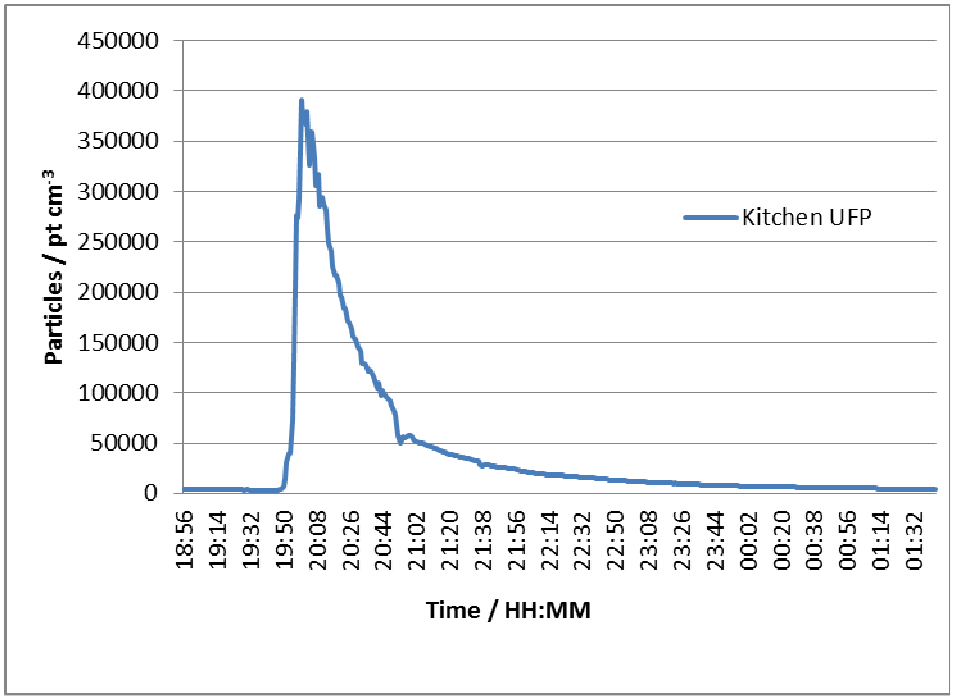
E.9.2 Ultrafine particles

Table E-25 shows a summary of the UFP data recorded over nearly 7 hours. The maximum of 391,167 pt cm^{-3} was observed during the cooking activity on the first day of monitoring, and the increase in UFP correlated with a rise in CO. Figure E-9 shows the sharp rise in UFP when the activity occurred, and the fall which takes around 5 hours to drop to levels seen prior to the activity.

Table E-25: Summary of UFP in CH1

	UFP (pt cm^{-3})
Maximum	391,167
Minimum	3,334
Average	40,109
Standard Deviation	74,192

Figure E-9: UFP levels in the kitchen of CH1



E.9.3 Nitrogen dioxide

The NO_2 tubes were exposed for 18 days (Table E-26). The highest NO_2 was observed in the kitchen, the living room has approximately three times that monitored in the bedroom, this may be due to the living room being the adjacent room to the kitchen.

Table E-26: Average nitrogen dioxide levels over 18 day's exposure in CH1

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	431	18.3
Living room	431	9.8
Bedroom	431	2.6

E.10 CH2

The monitoring was approximately performed over 1.5 days. The occupant reported spending the majority of time in the open plan designed living room and kitchen. There were four different reported cooking activities, three of which involved the gas hobs and during two of these the cooker hood was used on the low setting. The gas central heating was set on a timer for an hour in the morning and 5 hours in the evening.

E.10.1 Carbon monoxide

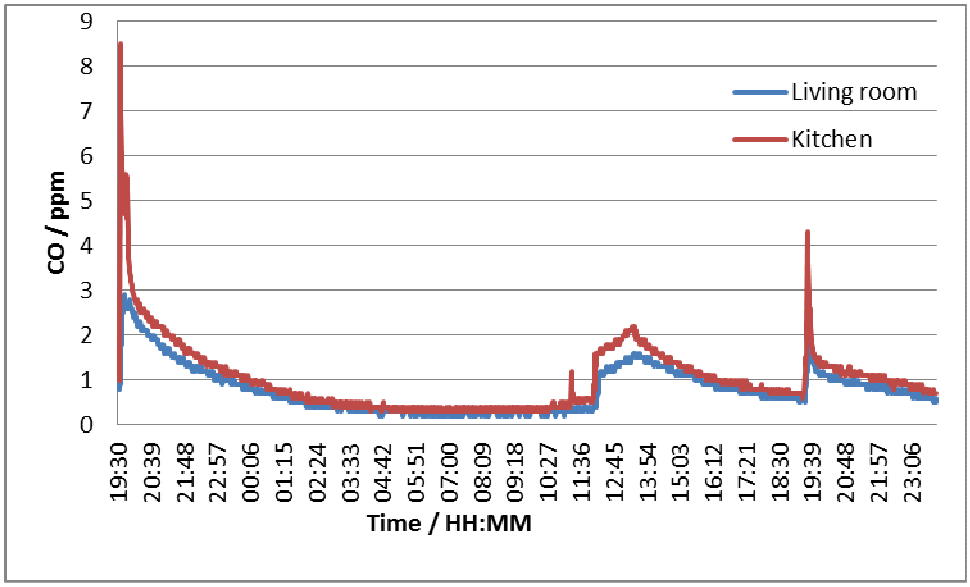
CO peaks recorded by the two kitchen monitors and the monitor in the living room were associated with the use of the gas hobs, Table E-27 gives the summary of the data monitored in CH2. The CO logger located by the hobs only ran for approximately the 12 hours and the CO logger in the bedroom did not record any levels of CO and 0 ppm was recorded throughout its operation, so its data is excluded from Table E-27. Where the highest recorded CO is observed for all monitors, two gas hobs were used for 30 minutes with the cooker hood also in operation. It takes a few hours for the monitors on the kitchen cupboard and in the living room to drop below 1 ppm after the cooking had ceased.

Table E-27: CO data from CH2

	Kitchen 1	Kitchen 2	Living room
Maximum	8.5 ppm	3.5 ppm	2.9 ppm
Minimum	0.3 ppm	0.0 ppm	0.2 ppm
Average	1.0 ppm	0.1 ppm	0.8 ppm
Standard deviation	0.8 ppm	0.4 ppm	0.5 ppm

Figure E-10 shows how the open plan design of the kitchen and the living room give the same trend but lower CO is observed in the living room compared to the kitchen.

Figure E-10: CO trend for Kitchen 1 and the living room monitor in CH2



E.10.2 Ultrafine particles

The UPC ran for 1.5 h, during which the cooking activity in which the maximum CO observed was monitored, Table E-28 summarises the data.

Table E-28: Summary of UFP in CH2

	UFP (pt cm^{-3})
Maximum	493,100
Minimum	25,540
Average	112,084
Standard Deviation	104,230

E.10.3 Volatile organic compounds

VOCs were monitored using diffusive Tenax tubes. The tubes were exposed for 13.8 days. Amounts of VOCs collected on the tubes were expressed as a concentration in air by applying a diffusive uptake rate value of 0.5 ml min^{-1}. From the chromatograms, the concentrations of the most distinguishable peaks were calculated and tabulated for each room (Table E-29). The bedroom has the highest TVOC measurement; this does not reflect combustion processes as there are no sources in the bedroom but is probably due to products used. In all three rooms, limonene has the highest measured concentration. Butyl acetate, 2-ethylhexan-1-ol and limonene have been quantified on the TD-GC-MS used in analysis, whereas decamethyl-cyclopentasiloxane (DMCPS) and $C_{12}H_{22}O_2$ are semi-quantified using the toluene calibration factor.

Table E-29: VOCs analysed on TD-GC-MS in CH2

	Bedroom (µg m^{-3})	Living room (µg m^{-3})	Kitchen (µg m^{-3})
TVOC	276	209	245
Butyl acetate	14	11	11
2-ethylhexan-1-ol	30	8	7
Limonene	54	52	53
DMCPS[a]	26	21	20
$C_{12}H_{22}O_2$[a]	15	11	11

[a]Semi-quantified

E.10.4 Nitrogen dioxide

The NO_2 tubes were exposed for 14 days (Table E-30). A tube was also set out in the living room but it was not retrieved.

Table E-30: Average NO_2 levels over 14 day's exposure in CH2

Tube location	Length of exposure (hours)	Average NO_2 ($\mu g\ m^{-3}$)
Kitchen	330	12.9
Bedroom	330	7.7

E.11 TW1

The monitoring was for approximately 1.5 days. This newly retrofitted home had whole house ventilation and combined heat recovery ventilation with natural passive stack ventilation. This uses the nature of warm moist air to rise through ducts and escape through the roof, where some of the heat of the escaping air is recovered to heat the outside air being drawn into the house. The gas hobs were reported to have been used on two different occasions during the monitoring period. On the second occasion, three hobs were on for a 2 hour period during a 3 hour cooking period. The central heating was set to come on for 3 hours in the morning, 2 hours in the afternoon and 3 hours in the evening, this may also affect combustion products observed, mainly those in the kitchen where the central heating is installed. The same system is also used to heat water for 2 hours in the morning, 2 hours in the afternoon and 2 hours in the evening where the heated water is stored in a tank in the bedroom.

E.11.1 Carbon monoxide

The CO logger placed in the living room only logged for the second half of the monitoring period. The maximum CO is observed in the kitchen, shortly before the maximum in the bedroom. The peaks coincide with a 3 hour cooking period using multiple hobs. At the time of these peaks, the living room CO monitor was not operating. The CO data for TW1 is summarised in Table E-31.

Table E-31: CO data from TW1

	Kitchen 1	Kitchen 2	Living room	Bedroom
Maximum	7.3 ppm	9.1 ppm	2.1 ppm	3.5 ppm
Minimum	0.8 ppm	0.0 ppm	0.5 ppm	0.0 ppm
Average	1.1 ppm	0.2 ppm	0.8 ppm	0.6 ppm
Standard deviation	0.6 ppm	1.0 ppm	0.3 ppm	0.4 ppm

E.11.2 Ultrafine particles

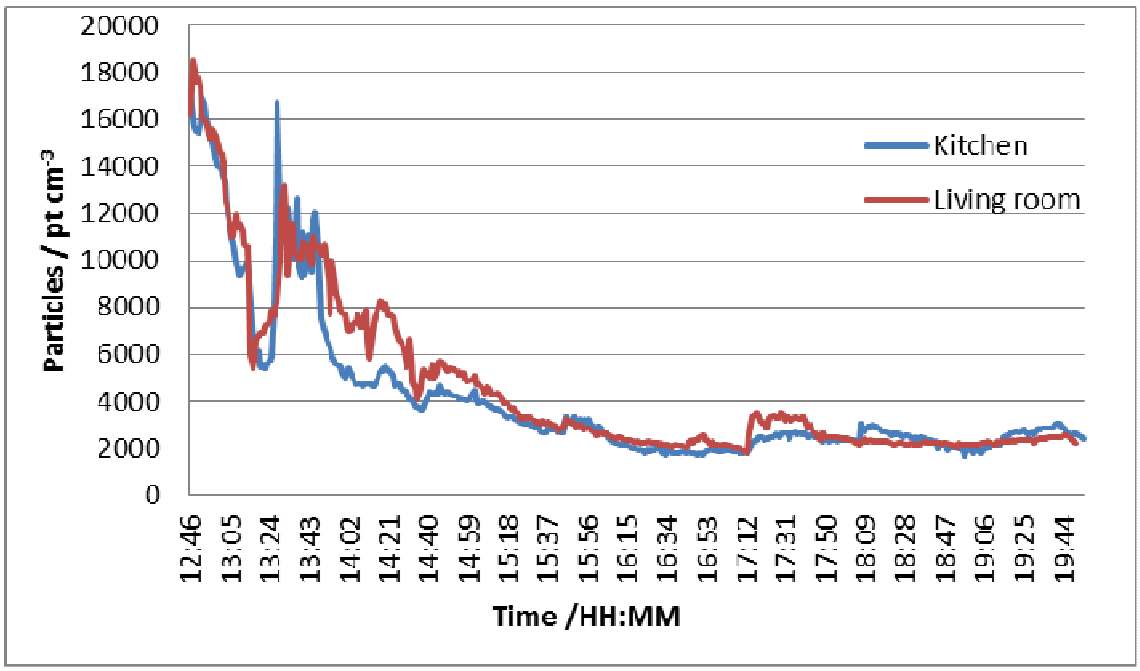
Two UPCs were used for monitoring the UFP in this house. One was located in the kitchen and the other in the living room where a biomass stove was located but the stove was not used in the monitoring period. Both of the monitors ran for 7 hours, during which a 20 minute cooking activity in which a single gas hob was used and the cooker hood was also operated on the low setting. A summary of the recorded UFP levels can be found in Table E-32. The UFP count does not seem to be greatly affected by the cooking activity, the maximum observed occurred during the first few minutes of the logging and the monitors are seen to fluctuate for the first couple hours of operation, during which the cooking occurred as well as drilling work.

Table E-32: Summary of UFP in TW1

	UFP (pt cm^{-3}) - kitchen	UFP (pt cm^{-3}) – living room
Maximum	17,198	18,480
Minimum	1,686	1,803
Average	4,160	4,616
Standard Deviation	3,348	3,564

As Table E-32 and Figure E-11 show similar levels and trends of CO concentration generally occurred in both rooms.

Figure E-11: UFP levels in the kitchen and living room of TW1



E.11.3 Volatile organic compounds

VOCs were monitored using diffusive Tenax tubes. Tubes were placed in the living room, bedroom and kitchen with two in each location. As with CH1, the concentrations of the most distinguishable peaks were calculated for each room and were averaged from the two tubes along with the TVOC value (Table E-33). The bedroom had the highest TVOC measurement and the kitchen the lowest. From Table E-33, α- pinene is the most abundant VOC in the bedroom, 2-phenoxyethanol, 2-chloropropane and DMCPS are more dominant in the kitchen than in the living room and may represent combustion processes. The gas boiler for the central heating was located in the bedroom that was monitored. The tubes were out for 15.1 days, calculations were assumed from an uptake rate of 0.5 ml min^{-1}.

Table E-33: VOCs analysed on TD-GC-MS in TW1

	Bedroom (µg m^{-3})	Living room (µg m^{-3})	Kitchen (µg m^{-3})
TVOC	1416	941	743
Texanol 1[a] Texanol 2[a]	81 111	64 90	57 78
α- pinene	296	85	49
2-chloropropane[a]	29	40	44
DMCPS[a]	33	41	34
Toluene	36	19	18
2-phenoxyethanol[a]	17	31	67
2,2,4-Trimethyl-1,3-pentanediol diisobutyrate	47	34	29

[a] Semi-quantified

E.11.4 Nitrogen dioxide

The NO_2 tubes were exposed for 15 days (Table E-34).

Table E-34: Average NO_2 levels over 15 day's exposure in TW1

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	362	22.8
Living room	362	21.3
Bedroom	362	23.7

E.12 LB1

The monitoring was for approximately 1.5 days. The living room was of open plan design with the kitchen. There was no combustion appliance in LB1; cooking, water heating and space heating were fuelled by electricity. The participant noted in the questionnaire that candles are burnt regularly in the home, approximately one per day. Two candles were reported to have been lit during the monitoring period in the activity diary.

E.12.1 Carbon monoxide

The living room had the highest observed CO. The small peaks in CO are observed in the periods where a candle is lit. The maximum observed in the kitchen and the bedroom is also in the period when the candle is lit. A summary of the data recorded in LB1 is given in Table E-35.

Table E-35: CO data from LB1

	Kitchen 1	Kitchen 2	Living room	Bedroom
Maximum	1.7 ppm	1.0 ppm	2.3 ppm	0.6 ppm
Minimum	0.4 ppm	0.0 ppm	0.6 ppm	0.0 ppm
Average	0.8 ppm	0.1 ppm	1.1 ppm	0.1 ppm
Standard deviation	0.4 ppm	0.3 ppm	0.5 ppm	0.2 ppm

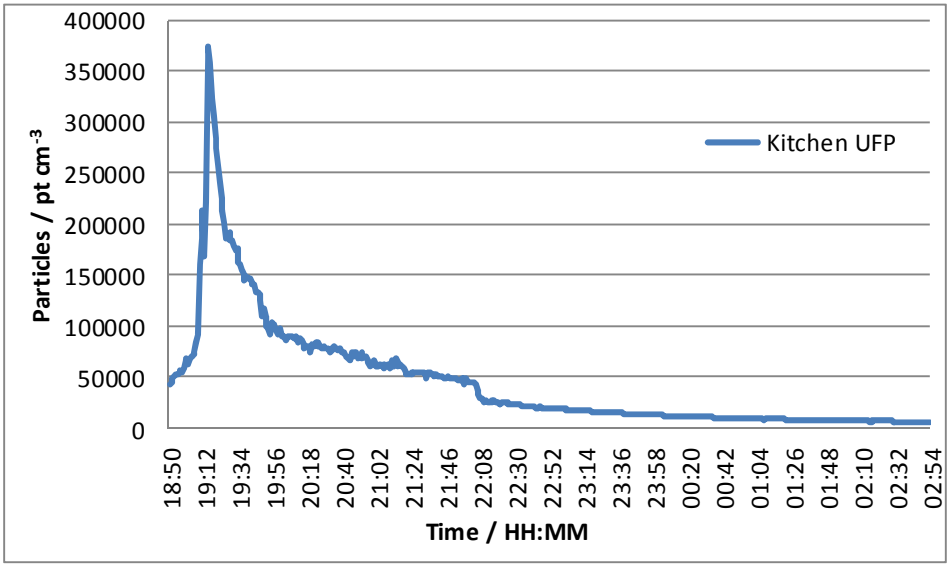
E.12.2 Ultrafine particles

When the UPC was turned on, levels were elevated at around 40,000 pt cm^{-3}, compared to the level recorded when the occupants had gone to their bedroom. A summary of the recorded UFP levels can be found in Table E-36. The initial concentration increased as the electric oven was used for approximately 15 minutes and a candle had been lit in the living room, levels stayed elevated for a few hours before declining eventually to around 5,000 – 6,000 pt cm^{-3}. These observations can be seen over time in Figure E-12.

Table E-36: Summary of ultrafine particles in LB1

	UFP (pt cm^{-3})
Maximum	373,416
Minimum	5,485
Average	45,795
Standard Deviation	56,916

Figure E-12: UFP levels in the kitchen of LB1



E.12.3 Nitrogen dioxide

The NO_2 tubes were exposed for 14 days (Table E-37).

Table E-37: Average NO_2 levels over 14 day's exposure in LB1

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	336	12.3
Living room	336	10.0
Bedroom	336	6.4

E.13 WS1

The monitoring was for approximately 1.5 days. During the monitoring period, the bedroom window was constantly left open whilst the kitchen and living room were shut throughout. Three separate gas cooking activities were monitored in this home, and during one of these an electric ventilation fan was used.

E.13.1 Carbon monoxide

The monitor placed in the bedroom did not deviate from 0 ppm, its data is not included in the Table E-38 of the recorded CO data from the kitchen and living room. The peak in the kitchen occurred during a period when two gas hobs were used and an electric ventilation fan in the kitchen was also switched on.

Table E-38: CO data from WS1

	Kitchen	Living room
Maximum	5.9 ppm	3.2 ppm
Minimum	0.6 ppm	1.4 ppm
Average	1.1 ppm	2.0 ppm
Standard deviation	0.7 ppm	0.5 ppm

E.13.2 Total volatile organic compounds

The PID ran for 8 hours and the data from this time is summarised in Table E-39. There was one activity recorded in the diary during the PID operation, which concerned using the gas hobs for half an hour when the cooker hood was also used. The PID did not record any values during this time and the maximum occurred towards the start of the PID operation.

Table E-39: Summary of TVOC in WS1

	TVOC (µg m^{-3})
Maximum	332
Minimum	0
Average	1
Standard Deviation	15

E.13.3 Nitrogen dioxide

The NO_2 tubes were exposed for 14 days (Table E-40).

Table E-40: Average NO_2 levels over 15 day's exposure in WS1

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	357	23.7
Living room	357	7.9
Bedroom	357	8.3

E.14 SA1

It was reported that the gas cooker was not usually used by the occupant and had not been serviced for a while. A cooking scenario was simulated initially where all monitors were placed around the kitchen, which involved bringing

water to the boil and replacing it to reduce steam build up and use of the oven. After this the monitors were set around the house for 2 days and no other activities were reported in the kitchen. The cooker did not have a cooker hood but an extract fan was located in the kitchen; when not in use it was an open wall vent. The property had the same heating schedule for space and water heating which was set for 2 hours in the morning and 5 hours in the evening.

E.14.1 Cooking scenario

ICOM 1 was set out above the cooker on a window ledge behind the cooker, ICOM 2, the UPC and the PID were placed on the worktop adjacent to the hobs and EL 1 & EL 2 were on the other side of the worktop further away from the appliance. The monitors were left for 10 minutes to record the background prior to any activity (except the EL which did not come on until the appliance had been in operation). The monitoring lasted for approximately 90 minutes, 40 minutes of which involved cooking activities on multiple gas burners and the oven. The average temperature was 26.6℃ in the room and the outside weather was still, warm and sunny. Also a can of butane lighter fuel was sprayed around the kitchen after the cooking operation to determine the room air exchange rate based on the decline in VOC concentration. Table E-41 shows the pollutant data for the scenario.

Table E-41: Pollutant data monitored during cooking scenario in SA1

	ICOM 1 (ppm)	ICOM 2 (ppm)	EL 1 (ppm)	EL 2 (ppm)	UFPs (pt cm^{-3})	VOCs (µg m^{-3})
Maximum	55.4	57.6	58.9	58.5	500,000	7,722
Minimum	1.0	1.2	0.0	0.3	7,523	0
Average	13.4	14.2	13.3	14.2	231,470	3,170
Standard deviation	15.2	16.2	17.6	17.1	233,925	2,739

Although no guidelines were exceeded, a modified version of the Scenario 2 letter (Appendix D) was sent out to the participant suggesting that the gas cooker is serviced as prolonged use may cause health guidelines to be exceeded. A summary of the CO monitored was attached, where the values of the maximum 15 minute, 30 minute, 1 hour, 8 hours and 24 hour concentrations recorded in the property were given along with the WHO indoor air guidelines as a comparison. These were 46 ppm, 35 ppm, 21 ppm, 3 ppm and 2 ppm respectively. The CO peaked just below 60 ppm when 3 hobs and the oven were in use. After half an hour, all the hobs and the oven were turned off and the backdoor was opened to ventilate the room. About 15 minutes after the cooking had ceased, a can of butane was sprayed in the kitchen and the external door was shut. As expected, the butane did not affect the CO readings. About an hour after the cooking period, the monitors were set in the kitchen, living room and the main bedroom. The UPC monitoring maximum of 500,000 pt cm^{-3} was reached for the majority of the cooking scenario and a plateau was observed for 30 minutes where the UFP count may have exceeded this value.

E.14.2 Carbon monoxide

From the activity diary, it is observed that when the hobs are used CO is produced which coincides with the maximum values observed and other peaks. At this point, all the monitors were situated in the kitchen. Therefore the two kitchen CO monitors which remained have their monitoring done over a slightly longer monitoring period, as the living room and bedroom monitors were set up afterwards. Apart from the one reported activity of the gas cooker, there was no other reported activities which may of caused elevated CO. Average CO levels are higher in the kitchen than the bedroom and the kitchen due to the one activity and the monitor in the bedroom did not record any levels and all data uploaded was 0.0 ppm (Table E-42).

Table E-42: CO data from SA1

	Kitchen 1	Kitchen 2	Bedroom	Living room
Maximum	55.4 ppm	57.6 ppm	0.0 ppm	1.5 ppm
Minimum	0.4 ppm	0.6 ppm	0.0 ppm	0.0 ppm
Average	1.4 ppm	1.7 ppm	0.0 ppm	0.3 ppm
Standard deviation	4.3 ppm	4.5 ppm	0.0 ppm	0.2 ppm

E.14.3 Ultrafine particles and total volatile organic compounds

The UPC ran for 8 hours and the maximum occurred during the one gas cooking activity, but levels decreased after this. A summary of the UFP data can be found in Table E-43, where the PID summary is also tabulated. The PID ran for 8 hours and the maximum occurred when a spray of butane was used. Using Equation 3-4 to calculate mean air exchange, a mean air exchange of 0.8 h^{-1} was calculated from the rate of decline in particles produced from a spray of a butane aerosol in SA1. This was done over a 15 minute period when the windows throughout the house and doors were shut in the room where the spray occurred.

Table E-43: Summary of UFPs and TVOCs in SA1

	UFP (pt cm^{-3})	TVOC (µg m^{-3})
Maximum	500,000	7,722
Minimum	4,445	0
Average	47,993	1,453
Standard Deviation	134,107	1,670

E.14.4 Nitrogen dioxide

The NO_2 tubes were exposed for 14 days (Table E-44). The tubes were not exposed until after the cooking scenario.

Table E-44: Average NO_2 levels over 14 day's exposure in SA1

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	339	25.1
Living room	339	20.4
Bedroom	339	15.1

E.15 SA2

SA2 was monitored for approximately 2.5 days, and 2 of these days were fully detailed in activity diaries. On the first day, ventilation via window opening only occurred for half an hour, whereas on the second day the bedroom window was opened for 10 hours and the property had the same heating schedule for space and water heating which was set for 2 hours in the morning and 5 hours in the evening.

E.15.1 Carbon monoxide

From Table E-45, the average CO concentration recorded by the four monitors are all below 1 ppm and the maximum was less than 5 ppm, with the monitors in the dining room having the largest maximum. The maximum occurs from use of a fire in the living room. The back boiler in the dining room when active did not seem to affect CO levels. From the activity diary, the electric cooker is used numerous times with the cooker hood being also used most of the times that the cooker is operated. As expected, the electric cooker does not affect the CO monitors. The monitor in the dining room on the gas fire did not seem to be affected by the pilot light and has the lowest average CO out of the four CO monitors.

Table E-45: CO data from SA2

	Kitchen 1	Living room	Dining room	Dining room
Maximum	2.1 ppm	1.7 ppm	4.5 ppm	4.0 ppm
Minimum	0.2 ppm	0.4 ppm	0.0 ppm	0.0 ppm
Average	0.8 ppm	0.7 ppm	0.5 ppm	0.2 ppm
Standard deviation	0.4 ppm	0.2 ppm	0.7 ppm	0.4 ppm

E.15.2 Particles and total volatile organic compounds

The UPC and the total particles monitor ran for 6 hours and were moved over multiple locations during their operation. The maximum concentration of particles was observed during a 10 second burst of a butane/propane propellant deodorant spray, and the levels soon dropped to less than 3 µg m^{-3}. This was also the cause of the maximum observed for the PID. The particles are elevated above the average level monitored during the cooking period. A summary of the UFP, total particle and PID levels can be found in Table E-46. The PID ran for 7.5 hours and was set out in the kitchen for its duration.

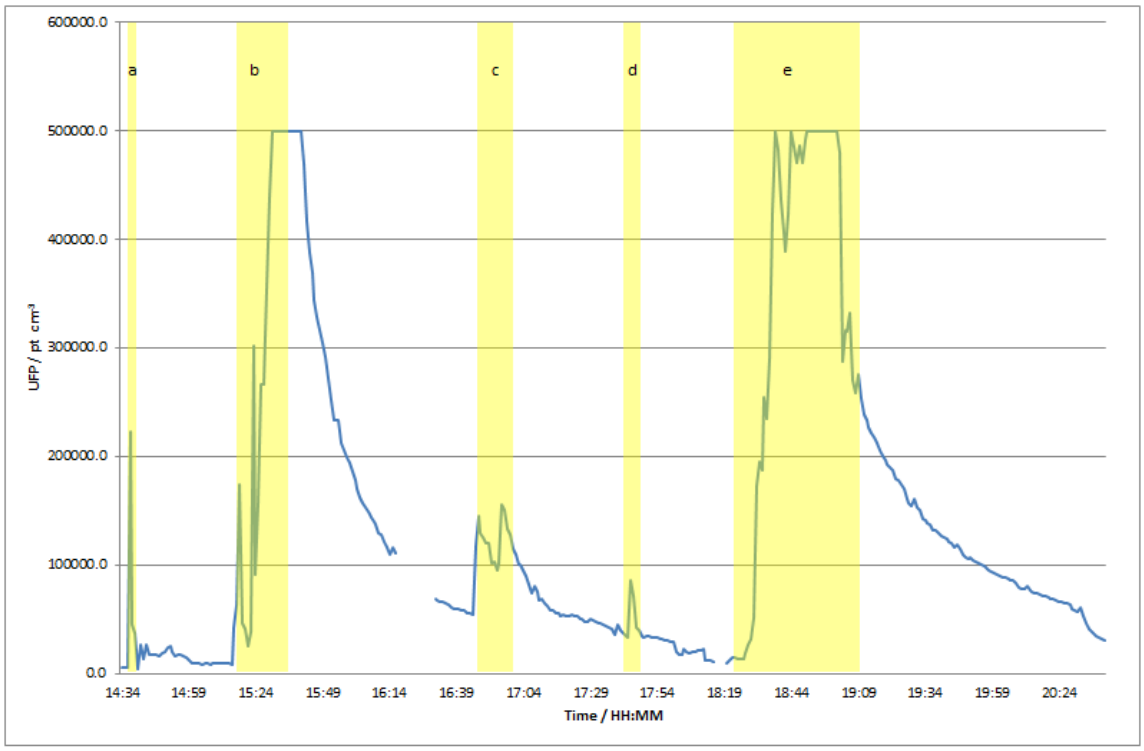
Table E-46: Summary of particles and TVOCs in SA2

	Particles (mg m^{-3})	UFP (pt cm^{-3})	TVOC (µg m^{-3})
Maximum	20.24	500,000	5,580
Minimum	0.01	3,705	0
Average	0.54	141,137	442
Standard Deviation	1.25	147,024	663

The UPC was exposed to various situations during its operation, its trend shown in Figure E-13 with annotations explained (the two breaks in data are due to

depleted battery power). The UFP maximum occurred during the operation of a gas fire and on a second instance where the UPC was exposed in the kitchen during a cooking activity when the oven and multiple hobs were used.

Figure E-13: UFP in various location and scenarios in SA2



a – Ceramic hob turned on near UPC (no pan), then briefly taken outside, where the level drops from a couple of hundred thousands to a couple of thousands.

b – Taken to the dining room, fire place turned on for shaded area.

c – Ironing in the room; increase in levels observed.

d – five minutes prior to d, taken to kitchen, 10 second spray of butane propellant hairspray used, no apparent effect on UFP levels, then the cooker hood was turned on. Increase in UFP found when 10 second spray of butane/propane propellant deodrant. Peak occurs a couple mins after the spray.

e – electric oven turned on and shortly after electric hob also, UFP increases to around 200,000 pt cm^{-3}. Levels shoot up to around 400,000 pt cm^{-3}. The cooker

hood is turned onto the low setting about 5 minutes before the 500,000 pt cm^{-3} limit is reached. The kitchen window is opened and the level drops below 500,000 pt cm^{-3}. Shortly after the electric cooking appliance is turned off, and the cooker hood and window is shut and the UFP decrease steadily until the monitor runs out of power.

E.15.3 Nitrogen dioxide

The NO_2 tubes were exposed for 16 days (Table E-47).

Table E-47: Average NO_2 levels over 16 day's exposure in SA2

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	381	13.9
Dining room	381	14.9
Bedroom	381	11.9

E.16 WV1

WV1 was monitored for approximately 1.5 days. The participant did not complete the activity diary fully as the cooking diary was completed but the ventilation and the time spent around the home was not completed. The property had a heating schedule for 3 hours in the morning and 5 hours in the evening, hot water was not on a schedule.

E.16.1 Carbon monoxide

From Table E-48, the maximum CO values from the four monitors were highest in the kitchen, and this occurred when the gas grill was used. During a three hour cooking activity in which the gas oven and gas hobs were used, the CO did not exceed 5 ppm. The bedroom and living room CO have averages of lower than 0.6 ppm, while the kitchen monitors have an average of 1.2 ppm, due to the gas appliances located in the room. The living room has a gas fire, but this was not used in the monitoring period.

Table E-48: CO data from WV1

	Kitchen 1	Kitchen 2	Bedroom	Living room
Maximum	11.5 ppm	10.3 ppm	2.0 ppm	2.0 ppm
Minimum	0.2 ppm	0.2 ppm	0.0 ppm	0.0 ppm
Average	1.2 ppm	1.2 ppm	0.2 ppm	0.5 ppm
Standard deviation	1.3 ppm	1.3 ppm	0.4 ppm	0.6 ppm

E.16.2 Particles

The UPC and total particle monitor ran for 1.5 hours and 3 hours respectively, both placed on the kitchen worktop. The UPCs maximum occurred during the operation of a gas grill. The particle monitors maximum occurred from the use of hairspray, which did not appear to affect the readings of the UPC. A summary of the recorded UFP and particle levels can be found in Table E-49.

Table E-49: Summary of particles in WV1

	Particles (mg m^{-3})	UFP (pt cm^{-3})
Maximum	1.41	499,600
Minimum	0.01	7,880
Average	0.08	210,059
Standard Deviation	0.11	156,553

E.16.3 Nitrogen dioxide

The NO_2 tubes were exposed for 21 days (Table E-50). Over the 21 days, the NO_2 is highest in the kitchen, the room where the most used combustion appliances are, suggesting that these are the major influencing factor on the levels of nitrogen dioxide in WV1.

Table E-50: Average NO_2 levels over 21 day's exposure in WV1

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	510	35.3
Living room	510	15.9
Bedroom	510	10.8

E.17 WV2

WV2 was monitored for approximately 1.5 days over which the participant reported that 100% of their time was spent at home and all windows were shut. The property has no specific water or space heating schedule, but had a thermostat to regulate the heat for the central heating system.

E.17.1 Carbon monoxide

From Table E-51, the average CO from the four monitors are 1 ppm or below, the maximum was observed in the kitchen and occurred during one of the three gas cooking activities over the monitoring period. Two of these activities involved using the oven, and levels did not exceed 2 ppm whereas the maximum of 14.2 ppm was observed during the use of the gas grill for 20 minutes.

Table E-51: CO data from WV2

	Kitchen 1	Kitchen 2	Living room	Bedroom
Maximum	14.2 ppm	8.5 ppm	1.6 ppm	2.3 ppm
Minimum	0.4 ppm	0.0 ppm	0.1 ppm	0.0 ppm
Average	1.0 ppm	0.2 ppm	0.8 ppm	0.2 ppm
Standard deviation	1.0 ppm	0.8 ppm	0.2 ppm	0.3 ppm

E.17.2 Total volatile organic compound

The PID ran for 3 hours, the data from this time is summarised in Table E-52. There were no reported activities during the operation of the PID.

Table E-52: Summary of TVOC in WV2

	TVOC (µg m^{-3})
Maximum	5,141
Minimum	0
Average	599
Standard Deviation	1,201

E.17.3 Nitrogen dioxide

The NO_2 tubes were exposed for 26 days (Table E-53). The kitchens value was double the level of that in the living room and the bedroom.

Table E-53: Average NO_2 levels over 26 day's exposure in WV2

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	654	73.3
Living room	654	36.2
Bedroom	654	35.7

E.18 CC1

CC1 was monitored for approximately 1.5 days. The participant worked from home and spent 100% of their time at home. It should be noted that the office was located externally to the house, but connected by a wall to the house. The gas hobs were reported to have been used on three different occasions during the monitoring period, with the cooker hood used on its highest setting each

time. Single gas burners were used on each of the three occasions, the participant did not write the times of the cooking period within the diary. The participant had also cooked shortly prior to when the monitors had been set out.

E.18.1 Carbon monoxide

From Table E-54, the maximum CO from the four monitors is highest in the kitchen, this occurred during one of the three gas cooking activities. The periods of the other two gas cooking activities gave slight rises in CO levels. The living room is connected by a door to the kitchen and it was after the cooking activity when the two kitchen monitors reached their maximums (12.3 and 7.3 ppm) that the living room reached its maximum of 3.0 ppm.

Table E-54: CO data from CC1

	Kitchen 1	Kitchen 2	Office	Living room
Maximum	12.3 ppm	7.3 ppm	1.5 ppm	3.0 ppm
Minimum	0.2 ppm	0.0 ppm	0.0 ppm	0.2 ppm
Average	0.9 ppm	0.2 ppm	0.2 ppm	0.8 ppm
Standard deviation	1.2 ppm	1.0 ppm	0.1 ppm	0.6 ppm

E.18.2 Ultrafine particles and total volatile organic compounds

The UPC ran for 1.5 hours and the PID ran for 6 hours, during which no activities were reported. A summary of the recorded UFP and PID levels can be found in Table E-55.

Table E-55: Summary of UFPs and TVOCs in CC1

	UFP (pt cm^{-3})	TVOC (µg m^{-3})
Maximum	43,305	860
Minimum	13,815	0
Average	24,688	9
Standard Deviation	7,919	65

E.18.3 Nitrogen dioxide

The NO_2 tubes were exposed for 14 days (Table E-56).

Table E-56: Average NO_2 levels over 14 day's exposure in CC1

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Kitchen	340	18.8
Living room	340	32.0
Bedroom	340	6.3

Appendix F Diffusive NO_2 lab report

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UKAS TESTING 2187

LABORATORY ANALYSIS REPORT

NITROGEN DIOXIDE IN DIFFUSION TUBES BY U.V. SPECTROPHOTOMETRY

REPORT NUMBER	42189
BOOKING IN REFERENCE No	D 5934
CUSTOMER	Cranfield University IEH, 1st Floor, Vincent Building, Cranfield University Cranfield, Bedfordshire MK43 0AL
DATE SAMPLES RECEIVED	12/11/2010

	Exposure Data					TOTAL
Tube Number	**Date On**	**Date Off**	**Time (hr.)**	**µg/m³ ***	**ppb ***	**µG NO_2**
376454 BR	22/10/2010	06/11/2010	362.67	2.81	1.47	0.07
376464 LR	22/10/2010	06/11/2010	362.67	7.82	4.08	0.21
376396 K	22/10/2010	06/11/2010	362.67	9.18	4.79	0.24
Lab Blank			362.67	0.11	0.06	0.003

Comment: Results are not blank subtracted
Results have been corrected to a temperature of 293K (20C)

Overall M.O.U.	10.93% +/-	**Limit of Detection**	0.011µgNO_2
Tube Preparation : 20% TEA / Water	Analysed on UVS03 Camspec M550	**Analyst Name**	Amy Le Ber
Date of Analysis	19/11/2010	**Date of Report**	19/11/2010

Analysis carried out in accordance with documented in-house Laboratory Method GLM7

The Diffusion Tubes have been tested within the scope of Gradko International Ltd. Laboratory Quality Procedures calculations and assessments involving the exposure procedures and periods provided by the client are not within the scope of our UKAS accreditation. Those results obtained using exposure data shall be indicated by an asterisk. Any queries concerning the data in this report should be directed to the Laboratory Manager Gradko International Ltd.

REPORT OFFICIALLY CHECKED

Gradko International Ltd
This signature confirms the authenticity of these results
Signed.....
L. Gates, Laboratory Supervisor

Appendix G Additional monitoring data

Table G-1 shows data monitored by the participant from SA2 for an hour long car journey, predominantly on the motorway with free flowing traffic, with one journey in the evening and one in the morning, both in winter. The summer car journey of the same route is also presented. Table G-2 has data for two 1.5 h car journeys from the participant of WV1; particles were monitored during a winter journey and CO during a summer journey. The journey was predominantly on the motorway with free flowing traffic in the late evening.

Table G-1: SA2 CO data for car journeys

	CO – winter evening (ppm)	CO – winter morning (ppm)	CO - summer evening (ppm)	CO - summer morning (ppm)
Maximum	1.5 / 2.2	3.2	1.3	1.3
Minimum	0.6 / 0.9	0.4	0.2	0.0
Average	0.9 / 1.3	0.7	0.5	0.4
Standard Deviation	0.2 / 0.3	0.4	0.3	0.2

Table G-2: Car journey WV1

	Particles - evening (mg m^{-3})	UFP - evening (pt cm^{-3})	CO – evening (ppm)
Maximum	0.19	101,673	1.1
Minimum	0.10	3,730	0.2
Average	0.12	31,382	0.5
Standard Deviation	0.01	19,534	0.2

Table G-3 shows VOCs monitored using pumped sampling with Tenax tubes in WV1, using an approximately half an hour sampling time both before and during cooking. One column shows data for VOCs before any cooking activity had occurred on the gas stove and the other column for VOCs monitored during cooking of roast chicken, where a gas oven and gas hobs were used. The data was sampled on a kitchen worktop surface approximately 1m high and 0.5m diagonally from the cooker. The most notable changes are the increase of limonene and a compound of molecular formula $C_{18}H_{12}O_2$ and a decrease DMCPS during cooking.

Table G-3: VOCs analysed on GC-MS in WV1

	Before cooking (µg m^{-3})	During cooking (µg m^{-3})
TVOC	239	263
Toluene	13	13
Ethylbenzene	12	12
m/p-xylene	40	37
Limonene	15	67
DMCPS[a]	70	35
Diethylaminopropyne	19	24
$C_{18}H_{12}O_2$[a]	n/a	189

[a]Semi-quantified

Table G-4 has NO_2 monitored in various locations other than inside the home, they include cars, an office, gardens and in student accommodation.

Table G-4: NO_2 in various locations (winter)

Tube location	Length of exposure (hours)	Average NO_2 (µg m^{-3})
Office	356	10.2
SA2 car	352	15.3
WV1 front garden	510	27.6
WV1 back garden	510	27.3
Student Halls - car	354	18.5
Student Halls - BR	354	16.0
Student Halls - K	354	46.6

Table G-5 shows particles monitored in the bedroom of WV1 during a 3.5 hours burning of an incense stick. The maximum UFP and total particles observed were found to be approximately an hour into the burning.

Table G-5: Summary of particle concentrations during burning of incense in bedroom of WV1

	Particles (mg m^{-3})	UFP (pt cm^{-3})
Maximum	0.21	114,183
Minimum	0.07	5,726
Average	0.12	46,132
Standard Deviation	0.03	33,581

Table G-6 shows the car journey data for an occupant of the pilot study home H1. The car journey to and from the participants' home was approximately 40 minutes in the evening and 35 minutes in the morning, suggesting more traffic

was encountered in the evening. The averages were the same for the journey but the range for the evening journey is wider as the maximum and the minimum are both larger and smaller. The route is mainly on the motorway with moderate traffic.

Table G-6: Summary of CO data from car journey for H1 (summer)

	CO (ppm)	CO (ppm)
Maximum	1.5	1.1
Minimum	0.3	0.6
Average	0.7	0.7
Standard Deviation	0.2	0.1

Table G-7 shows data from an office in Cranfield University, over a 1 hour period. The office does not have any source of combustion, it has computers, printers etc. and is ventilated mechanically.

Table G-7: Office CO summer 1 hour

	CO (ppm)
Maximum	0.4
Minimum	0.0
Average	0.2
Standard Deviation	0.1

Table G-8 shows data over a 4 hour period in the bedroom of student accommodation where a 10 second spray of a butane propellant was used in a room where all windows and doors were shut. Air exchanges were calculated

using Equation 3-4 with the monitored data from the PID and were found to range from 0.1 - 1 $h^{-1,}$ the estimated average over the 4 hour period was 0.4 h^{-1}.

Table G-8: Particles and VOCs during a 4 hour period after use of a butane spray

	Particles (mg m^{-3})	UFP (pt cm^{-3})	VOC (ug m^{-3})
Maximum	3.78	62,722	7,310
Minimum	0.05	2,419	0
Average	0.56	11,735	4,401
Standard Deviation	0.66	11,468	1,606

Appendix H Poster presented at Annual Review Meeting on Indoor and Outdoor Air Pollution Research 10 & 11 May 2011

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Cranfield Health

Risks to health of carbon monoxide and other combustion gases in energy efficient homes

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Introduction

Revisions of the UK building regulations introduced to help combat climate change are resulting in changes in the design & construction of new & refurbished homes, as well as methods of heating & ventilation. This could lead to new/increased risks to health of occupants because of inadequate ventilation & increasing levels of indoor pollutants such as those generated by combustion appliances. This project is measuring combustion related indoor pollutants in a sample of 15 new homes & some older homes to assess possible risks to occupant health.

Methods/Materials

Air pollutants have been monitored in new/retrofit homes during the 2010/11 heating season with unobtrusive monitors.

- Measurements of CO, NO_2, particulates, including ultrafine particles (UFP), & some organic compounds in air in the kitchen & other habitable rooms.
- Activity diaries kept over two main days of the monitoring period in which continuous measurements of CO, particulates & VOCs were taken. Diffusive NO_2 sampling was over 2 weeks.
- Comparisons to health based guidelines are made to determine if the monitored levels are a potential risk to human health & well being.

Results

Table 1 provides results for 6 properties (5 newly built/retrofit & 1 older home).

Table 1. Properties of 6 homes monitored & summary of pollutant concentrations in the kitchens

Home	Year built / age band	Build type	Main cooking appliance fuel	Main heating appliance fuel	Cooker hood? / (used)[b]	Maximum CO (ppm)[b]	Mean CO (ppm)[b]	Maximum 1 & 8 hour CO (ppm)[c]	NO_2 (µg m^{-3})	Maximum UFP (pt cm^{-3})[d]	Mean UFP (pt cm^{-3})[d]
I	2010	Semi-detached	Gas & electric	Gas	Yes / (yes)	13.9	0.7	4.8 & 1.7	9.2	7,360	5,008
II	2010	End terrace	Gas & electric	Gas	Yes / (yes)	10.7	0.7	3.9 & 1.1	11.2	500,000[e]	46,103
III	2007	2nd floor flat	Electric	Gas	Yes / (no)	1.6	0.9	1.5 & 1.1	12.0	315,683	119,075
IV	1945-1964[a]	Semi-detached	Gas & electric	Gas	Yes / (yes)	9.1	0.8	4.2 & 1.7	22.8	17,198	4,160
V	2010	1st Floor flat	Gas & electric	Gas	Yes / (yes)	8.5	1.0	3.6 & 1.4	12.9	493,100	112,084
VI	1965-1975	Semi-detached	Gas	Gas	No / (n/a)	58.9	1.7	21.4 & 3.9	25.1	500,000	47,993

[a] Retrofit 2010/11 [b] continuously logged data (approximately 2 days) [c] WHO time weighted average guidelines: 26 ppm (1 hour) 9 ppm (8 hours)
[d] continuously logged data (approximately 8 hours) [e] 500,000 pt cm^{-3} is the maximum range of the UFP monitors

- NO_2 levels in all 6 homes were well below the WHO annual average guideline (40 µg m^{-3}).
- Maximum UFP readings monitored in the 6 homes ranged from 7,360 pt cm^{-3} (no reported activity during operation of the monitor) to >500,000 pt cm^{-3} (gas cooking reported). There are no recommended guidelines for exposure limits.
- No WHO guidelines for CO were exceeded in the monitoring of the 6 homes.
- Home VI had an old gas cooker which caused the maximum concentration observed during a 40 minute cooking activity. Although no guidelines were exceeded, the occupant was informed of the findings & recommended to service the appliance as extended use may cause exposure to harmful levels of CO.

Conclusions

Work is continuing to complete monitoring of 15 energy efficient homes & some older homes. Initial results for the 6 homes found guidelines not to be exceeded but the potential of an old cooker to generate elevated levels of CO was shown.

Computer modelling will also be applied to further explore scenarios & their risks to health. While only a preliminary investigation, the study is providing valuable indicative data & a basis for recommendations for further work.

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